APPENDIX A

GLOSSARY OF TERMS

This page intentionally left blank.

APPENDIX A

GLOSSARY OF TERMS

accident environment—Conditions resulting from an accident scenario, such as blast overpressures, fragments, and fire.

accident initiating condition—First launch vehicle system-level indication that results in a catastrophic accident.

aerobrake—Technique that uses atmosphere to reduce a spacecraft orbital period.

aeroentry subsystems—Equipment and systems used by the MS 01 lander/rover spacecraft when entering the Martian atmosphere.

affected environment—A description of the existing environment that could be affected by the Proposed Action.

ambient air—The surrounding atmosphere, usually the outside air, as it exists around people, plants, and structures. (It is not the air in the immediate proximity of the emission source.)

background radiation—Ionizing radiation present in the environment from cosmic rays and natural sources in the Earth; background radiation varies considerably with location.

backshell—Protective shell on back half of the MS 01 lander/rover spacecraft.

Becquerel (Bq)—Unit of activity equal to 1 disintegration per second, or 2.70×10^{-11} curies.

Biological and Conference Opinion—Documents formal consultations between a Federal Agency and the U.S. Fish and Wildlife Service under Section 7 of the Endangered Species Act. It provides a formal opinion from the U.S. Fish and Wildlife Service regarding impact or potential consequences to endangered or threatened species from a Proposed Action.

composite accident scenario—Grouping of initiating accident conditions and associated events having similar characteristics of location (e.g., near-pad or at-altitude); impact velocity range, and potential for dispersion of launch vehicle and spacecraft components.

conditional probability—Within the context of this DEIS, the probability that a release of radioactive material could occur given an initiating accident (i.e., the accident has occurred).

convection—Atmospheric motions that are predominately vertical, resulting in vertical transport and mixing of atmospheric properties.

criteria pollutants—The Clean Air Act required the U.S. Environmental Protection Agency to set air quality standards for common and widespread pollutants after preparing "criteria documents" summarizing scientific knowledge on their health effects. Today there are standards in effect for six "criteria pollutants": sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter equal to or less than 10 microns in diameter (PM_{10}), nitrogen dioxide (NO_2), ozone (O_3), and lead (Pb).

cruise stage—Spacecraft system used in the cruise phase of an interplanetary trajectory.

cryogenic [fuel]—Low temperature liquefied fuels (e.g., liquid oxygen (LOX) or liquid hydrogen (LH).

cultural resources—Prehistoric and historic districts, sites, buildings, objects, or any other physical activity considered important to a culture, subculture, or a community for scientific, traditional, religious, or any other reason.

cumulative impact—The impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes other such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time.

curation—Taking charge or management of specific material (e.g., extraterrestrial material).

curie (Ci)—A measure of the radioactivity level of a substance (i.e., the number of unstable nuclei that are undergoing transformation in the process of radioactive decay); one curie equals the disintegration of 3.70×10^{10} (37 billion) nuclei per second and is approximately equal to the radioactivity of one gram of radium-226.

decibel (dB)—A measurement unit that describes a particular sound pressure quantity to a standard reference value.

Delta—A family of space launch vehicles manufactured by the Boeing Company.

dose (biological)—The amount of energy from ionizing radiation deposited within tissues of the body; it is a time-integrated measure of potential damage to tissues from exposure to radiation and as such is related to health-based consequences.

equatorial landing location—Landing site close to the equator (on Mars).

expectation case—The outcome (source term; dose; health effects; land contamination) that would be anticipated if an accident were to occur which released radioactive material from the MS 01 lander/rover spacecraft; the expectation case is a statistical expression of probability-weighted consequences.

exposure to radiation—The incidence of radiation from either external or internal sources on living or inanimate material by accident or intent.

extraterrestrial material—Material other than of Earth.

first stage—Launch vehicle stage that provides initial thrust at lift-off.

geology—The study or science of the Earth (or any solid celestial body), its history, and its life as recorded in the rocks.

graphite epoxy motor (GEM)—Family of solid rocket motors with graphite/epoxy-wound casings containing solid fuel that augment the launch vehicle main engine booster capabilities.

haulout—An area where marine mammals haul themselves from oceans to congregate, breed, etc.

heatshield—The portion of the protective shell that protects a spacecraft from heat during atmospheric entry.

health effects—Within the context of this DEIS, health effects are defined as the number of additional, or excess, fatal cancers (above and beyond those that would normally be expected in the exposed population over a 50-year period).

hydrazine (N_2H_4)—A toxic, colorless liquid propellant that is spontaneously hypergolic in combination with nitric acid and concentrated hydrogen peroxide. Vapors may form explosive mixtures with air.

hypergolic—Igniting upon contact of components without external aid; of, relating to , or using hypergolic fuel.

infrared radiation—Electromagnetic radiation whose wavelengths lie in the range from 0.75 or 0.8 micrometer (the long-wavelength limit of visible red light) to 1,000 micrometers (the shortest microwaves).

initiating probability—The probability that an identified accident scenario and associated adverse conditions (accident environment) will occur.

instantaneous impact point (IIP)—The point on the Earth's surface that a launch vehicle would impact should an abort occur prior to orbital insertion.

interplanetary trajectory—Spacecraft's path from one planet to another.

isotopes—Forms of the same chemical element that differ only by the number of neutrons in their nucleus. Most elements have more than one naturally occurring isotope. Many isotopes have been produced in reactors and scientific laboratories.

lander—A spacecraft that is designed to land on a planet's surface.

maximally exposed individual—A hypothetical person that would receive the maximum possible dose.

mean—See expectation case.

mesosphere—The atmosphere layer between 44-55 kilometers and 80-95 kilometers, extending from the top of the stratosphere to the mesopause; characterized by a temperature change that generally decreases with altitude.

meteorology—Science that studies with atmospheric phenomenon or scientific study of atmospheric phenomenon.

mineralogy—Scientific study of minerals, their crystallography, physical and chemical properties, and classification.

morphology—A branch of biology that deals with structure and form of an organism at any state of its life history.

National Ambient Air Quality Standards (NAAQS)—Section 109 of the Clean Air Act requires the U.S. EPA to set nationwide standards, the NAAQS, for widespread air pollutants. Currently, six pollutants are regulated by primary and secondary NAAQS: carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone, and particulate matter equal to or less than 10 microns in diameter (PM_{10}), and sulfur dioxide (SO_2).

99^{th} Percentile Case—A statistical expression of the outcome (source term; dose; health effect; land contamination) that would occur not more than 1 percent of the time; the 99^{th} percentile case is derived from the distribution of outcomes developed for the Expectation Case; i.e., 1 percent of the outcomes were greater than the 99^{th} percentile level.

nitrogen oxides (NO_X)—Gases formed primarily by fuel combustion, which contribute to the formation of acid rain. Hydrocarbons and nitrogen oxides combine in the presence of sunlight to form ozone, a major constituent of smog.

nitrogen tetroxide(N_2O_4)—A liquid oxidizer that can cause spontaneous ignition with many common materials such as, paper, leather, or wood. It also forms strong acids in combination with water, and contact can cause severe chemical burns. It is a yellow-brown liquid which is easily frozen or vaporized.

No-Action Alternative—The alternative where current conditions and trends are projected into the future without the Proposed Action.

off-site—The area outside the property boundary of the CCAS or VAFB site.

on-site—The area within the property boundary of the CCAS or VAFB site.

orbital debris—All earth-orbiting objects except functioning satellites or spacecraft.

orbiter—Spacecraft that is designed to orbit a planet without landing.

payload—The element(s) that a launch vehicle or spacecraft carries over and above what is necessary for the operation of the vehicle in its fight. For a launch vehicle, the spacecraft being launched is the payload; for a scientific spacecraft, the suite of science instruments is the payload.

payload fairing (PLF)—Protective shell on a launch vehicle that encapsulates the spacecraft through atmospheric ascent.

peak concentration/mean concentration—The peak concentration is the highest reading in a series of samples; the mean concentration is the average of readings in a series of samples.

petrology—The branch of geology concerned with the origin, composition, and structure of rocks.

precision landing—Landing safely with specified accuracy at a given location.

radiation—The emitted particles (alpha, beta, neutrons) or photons (gamma x-ray) from the nuclei of unstable (radioactive) atoms as a result of radioactive decay. Some elements are naturally radioactive; others are induced to become radioactive by bombardment in a nuclear reactor or other particle accelerator. The characteristics of naturally occurring radiation are indistinguishable from those of induced radiation.

radioactive half-life (T 1/2)—The time required for one half the atoms in a radioactive substance to decay.

radioisotope heater unit (RHU)—A passive heating device that uses the radioactive decay of plutonium-238 dioxide to produce heat.

Relationship of Short-Term Uses and Long-Term Productivity—The balance or trade-off between short-term uses and long-term productivity need to be defined in relation to the Proposed Action.

rem—The unit dose representing the amount of ionizing radiation needed to produce the same biological effects as one roentgen of high-penetration X-rays (about 200 Kv).

RHU aeroshell—Shell that protects the RHU graphitics.

rover—A vehicle that can move freely on a planet's surface.

saltation—Sand grains that appear to hop or jump due to strong wind action, liftoff.

second stage—Launch vehicle stage that provides thrust during ascent, but not at liftoff.

sievert (Sv)—The SI unit of dose equivalent. One Sv is equivalent to 100 rem.

source term—The quantities of materials released during an accident to air or water pathways and the characteristics of the releases (e.g., particle size distribution, release height and duration); used for determining accident consequences.

sol—One day on a planet other than Earth (i.e., the time it takes the planet to rotate 360 degrees on its polar axis); on Mars, one sol is equal to 24 hours, 37 minutes or 1.026 Earth days.

spacecraft aeroshell—Protective shell that encapsulates the MS 01 lander/rover spacecraft.

stratopause—The boundary between the stratosphere and the mesosphere.

stratosphere—An upper portion of the atmosphere above the troposphere reaching a maximum height of 50 km (27 nmi) above the Earth's surface. The temperature is relatively constant in the lower stratosphere and gradually increases with altitude. The stratosphere is Earth's main ozone producing region.

thermal protection system—A combination of systems that protect a spacecraft from potential heat sources.

trajectory—The flight path that a spacecraft will take during a mission.

tropopause—The boundary between the troposphere and stratosphere, usually characterized by an abrupt change of lapse rate; the change is in the direction of increased atmospheric stability from regions below to regions above the tropopause; its height varies from 15 kilometers in the tropics to about 10 kilometers in polar regions.

troposphere—The portion of the atmosphere next to the Earth's surface in which the temperature rapidly decreases with altitude, clouds form, and convection is active. The troposphere begins at ground level and extends to an altitude of 10 to 12 km (5 to 6 nmi) above the Earth's surface.

unavoidable adverse effects—Effects that can be avoided due to constraints in alternatives. These effects must be disclosed, discussed and mitigated, if practicable.

upper stage—Launch vehicle stage that provides thrust required to insert a spacecraft into an interplanetary trajectory.

APPENDIX B

ENVIRONMENTAL EFFECTS OF RADIOACTIVE SOURCES ON THE MS 01 MISSION

This page intentionally left blank.

APPENDIX B

ENVIRONMENTAL EFFECTS OF RADIOACTIVE SOURCES ON THE MS 01 MISSION

This appendix addresses the potential impacts of the radioactive sources released to the environment, which could occur in any of the representative, low probability accident scenarios described in Chapter 4.0. The health and environmental risks associated with plutonium (mainly Pu–238) dioxide (PuO_2) were previously addressed in the Galileo, Ulysses, and Cassini EIS's (NASA 1989; NASA 1990; NASA 1995; NASA 1997).

In addition to the 3.69×10^{12} becquerels (Bq) (99.6 curies) (Ci) of Pu–238 that are contained in the 3 Light-Weight Radioisotope Heater Units (LWHRUs), there are also 3.70×10^{9} Bq (0.100 Ci) of curium–244 (Cm–244) in the Alpha Proton X-Ray Spectrometer, 1.30×10^{10} Bq (0.350 Ci) of cobalt–57 (Co–57) in the Mossbauer Spectrometer, less than 1.11×10^{6} Bq (30 microcuries (μCi)) of americium–241 (Am–241) in Mars Experiment on Electrostatic Charging (MEEC), and 7.4×10^{5} Bq (20.0 μCi) of curium–242 (Cm–242) in the radiation monitor. These radioactive materials can also be released during an accident involving the Mars 2001 Lander/Rover spacecraft.

The purpose of this appendix is to describe qualitatively the factors that influence the movement of Pu–238, Cm–244 and Co–57 through the environment and into the human body, together with the subsequent health effects. The Am–241 and Cm–242 are not specifically discussed because they are present in such minute quantities.

B.1 CHEMICAL AND PHYSICAL PROPERTIES THAT ARE IMPORTANT FOR BEHAVIOR IN THE ENVIRONMENT AND THE HUMAN BODY

In this section, the following important characteristics are discussed:

- Chemical form;
- Particle size distribution;
- Half life; and
- Decay modes.

B.1.1 Chemical Form

In the spacecraft, the Pu–238 is present as the dioxide. The Cm–244 and the Co–57 are present as metals. The predominant risk pathways are those in which these materials are released as the result of fire or through vaporization upon reentry. It is therefore assumed that the Pu remains oxidized and that the Cm and Co become oxidized. This is important because the chemical form influences the solubility, which in turn strongly influences such factors as bioaccumulation and uptake in the human body.

B.1.2 Particle Size Distribution

It is also important to understand the physical form of the material, in particular the particle size distribution, which influences, among other things: whether the material will fall to the ground in the immediate vicinity of the accident or will be transported over long distances; solubility in water and in biological fluids; and whether or not the material can be inhaled and where it will be deposited and retained within the human respiratory system.

The initial particle size distribution is a function of the conditions of the accident. For example, the launch area source terms would initially be in the form of vapor as a result of exposure to fire. The vapors would contain not only the radionuclides but also various structural materials. The radionuclides would tend to condense with and agglomerate with these other materials, which would then predominantly determine the characteristics of the aerosol. Thus, the accident analysis in U.S. DOE (1999) uses launch area source terms in which the vapor is agglomerated on Al_2O_3 particles, 70% of which have a physical diameter of 0.1 μm and 30% of which have a physical diameter of 1.0 μm. This is significant for at least two reasons: a) the size distribution is independent of the radionuclide and b) all of the particles are within the respirable range. The potential for uptake of inhaled particles is critically dependent on the size of the particles (respirable particles are considered to be 10 μm or less in size).

B.1.3 Half Lives

The half lives are as follows: Co–57, 271 d (0.73 yr); Pu–238, 87.8 yr; Cm–244, 17.9 yr. These half lives are particularly important for chronic exposure pathways. Clearly, most of the Co–57 will decay out of the environment in a small fraction of a human lifetime (70 yr.), whereas more than half of the Pu–238 will still be present after that time, together with about 10% of the Cm–244.

B.1.4 Decay Modes

Both Cm–244 and Pu–238 are α-emitters with decay energies of about 5 Mev. Their radioactive daughters are also α-emitters with about the same decay energy. These α-particles are what predominantly determine the effects on the human body. Cm–244 and Pu–238 can also undergo spontaneous fission, but in both cases the branch probabilities are extremely small.

Co–57 decays by electron capture and emits gamma (γ)-rays. These are of relatively low LET (linear energy transfer).

B.2 PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE RADIONUCLIDES AND THEIR TRANSPORT THROUGH THE ENVIRONMENT

B.2.1 Plutonium Dioxide

Plutonium is one of the most widely studied elements in terms of chemistry and environmental behavior. Although its chemistry and oxidation states are quite diverse,

the element's environmental mobility is very limited (INSRP 1989). The pathways and the generalized behavior of Pu–238 in the environment are described in the literature (e.g., Aarkrog 1977; Anspaugh et al. 1975; Pinder and Doswell 1985; Pinder et al. 1987; Yang and Nelson 1984).The extent and magnitude of potential environmental impacts caused by PuO_2 releases depend on the mobility and availability of PuO_2 and are directly controlled by a number of physical and chemical parameters, includIing particle size, potential for suspension, deposition and resuspension, solubility, and oxidation state of any dissolved plutonium. These factors, in conjunction with the three potential exposure pathways (i.e., direct external exposure from ground-deposited material, ingestion, and inhalation), determine the potential impacts.

In general, PuO_2 is insoluble and is poorly transported in aquatic, marine, and terrestrial environments. Most forms of plutonium, including PuO_2, are removed from biological pathways by processes such as sedimentation and fixation in soil. Only small amounts of material would be concentrated by biological accumulation into seafood, grazing animals, and other food products.

The size of plutonium dioxide particles can affect the rate of dissolution in water (including biological fluids, such as in the lungs or gastrointestinal tract) and the initial deposition and subsequent resuspension of particles in both air and water. The dissolution, suspension and resuspension potential ultimately control the mobility and availability of PuO_2 to plant and animal species including humans. Generally speaking, larger particles have less potential for suspension and resuspension; as the particle size decreases, particles are more easily kept in suspension.

A number of factors affect the solubility of PuO_2 in water. Physiological parameters most important to the solubility of PuO_2 are the reactive surface area and oxidation state of plutonium and the water chemistry, including pH, reduction/oxidation potential, and temperature. The mass to surface area ratios of particles affect the reactivity and solubility, with solubility being inversely related to particle size. The dissolution rate of the PuO_2 fuel is very small, ranging from 1.2 to 90 $\mu Ci/m^2/s$ (0.1 to 7.3 $\mu g/m^2/s$) in seawater and freshwater, respectively, based upon the dissolution rate per unit surface area of the fuel (NASA 1990; INSRP 1990). In general, PuO_2 is insoluble.

Because PuO_2 is so insoluble, movement through the environment depends on physical processes. PuO_2 may be carried into the soil by a number of routes, including the percolation of rainfall and subsequent leaching of particles into the soil, animal burrowing activity, and plowing or other disturbance of the soil by humans. Migration of the PuO_2 into the soil column is of concern, primarily because of the potential for PuO_2 to reach groundwater aquifers used as drinking water supplies. Once deposited on soil, however, PuO_2 appears to be extremely stable. Soil profile studies have shown that generally more than 95 percent of the PuO_2 from nuclear weapons fallout remained in the top 5 cm (2 inches) of surface soil (in undisturbed areas) for 10 to 20 years following deposition (USDOE 1987).

In marine and aquatic systems, larger particles would quickly settle to the bottom sediments; smaller silt-size particles may remain in suspension within the water column for extended periods of time. Smaller particles may not even break the water surface

(due to surface tension), forming a thin layer on the water surface that is subsequently transported to the shoreline by wind and wave action. Resuspension of smaller particles from the bottom could occur due to physical disturbance of the sediments by wave action and recreational uses of the water bodies (e.g., swimming, boating, and fishing), as well as by the feeding activity of various marine and aquatic species. Particles of PuO_2, as a component of the bottom sediments, may also be transported toward and along the shoreline by wave action and currents in near-shore environments (NASA 1990).

Studies have indicated that bioaccumulation in marine organisms can range from 2 to 3,000 depending on the type and population densities of seafood species impacted (e.g., freshwater fish, saltwater fish, mollusca), the amount and particle size distribution of radioactive material released, and the deposition area.

PuO_2 entering into a water/sediment system would be preferentially taken out of solution and bound in saturated sediments in amounts on the order of 100,000 times greater than the amounts that would remain in the associated water column (NASA 1990).

Clays, organics, and other anionic constituents tend to bind most of the PuO_2 particles in the soil or sediment column. The binding of PuO_2 usually occurs in the first few centimeters of sediment, greatly reducing the concentration of this constituent with depth. This natural filtering of PuO_2 would probably reduce the concentrations in drinking water to levels below the Primary Drinking Water Standard of 4 mrem/year (NASA 1990).

It is also possible that surface water runoff containing PuO_2 could directly contaminate drinking water supplies from surface water bodies, because this type of contamination is primarily due to suspended PuO_2 particles and not from dissolved PuO_2. Filtering the surface water before chemical treatment would reduce the concentration of total plutonium to very low levels (NASA 1990).

B.2.2 Curium

The behavior of curium in the environment has been much less studied than has that of plutonium. There is a somewhat greater body of studies on americium, which is chemically similar to curium. It does appear that oxides of curium and americium are more soluble than is PuO_2 and this is reflected by the fact that predicted bioaccumulation factors and the fraction of curium that enters the bloodstream after ingestion are an order of magnitude or two higher than for plutonium (see Tables B-1 and B-2). Table B-1 summarizes various environmental transfer factors obtained from a report by Strenge and Peterson (1989). These represent parameters obtained after extensive review of existing databases for use with MEPAS, the U.S. DOE's Multimedia Environmental Pollutant Assessment System. Table B-2 shows the ingestion and inhalation factors that were used for the Mars Mission study, based upon models developed by the International Commission on Radiological Protection (ICRP).

Table B-1 also shows data for Am–241, for completeness.

Laboratory studies on actinides in marine systems (Choppin and Morse 1987) show that the III, IV, and V oxidation states of actinides have “significant” sorption from seawater onto carbonate and oxide surfaces. This means that, as described above for PuO_2(IV), curium oxide (III) is also likely to be bound on clays, organics and other anionic constituents in the soil column, and to be predominantly removed to sediments in aquatic environments.

B.2.3 Cobalt

Radioisotopes of cobalt were produced from structural materials during nuclear tests, principally Co–60, with a half-life of 5.7 years (compared with 0.73 years for Co–57). Numerous studies of the behavior of fission products and actinides in the Marshall Islands have been performed over the years. Because many of these studies were performed in the context of resettlement many years after the tests, the Co–60 was relatively unimportant because several half-lives had elapsed. However, there is some useful information. For example, Noshkin et al. (1997) reviewed the concentrations of cesium–137, Co–60, and bismuth–207 in flesh samples of reef and pelagic fish collected from Bikini and Enewetak Atolls between 1964 and 1995. They found that the effective half-life of Co–60 in the lagoons was, to within the experimental error, equal to the radiological half-life. Since the principal means of removal from the lagoons is the transport of suspended or dissolved materials over the reefs or through the passes into the north equatorial Pacific water mass, this indicates that the Co–60 must be strongly bound to sediment. Most Co accumulated by fishes must be derived from food and sedimentary particles passing through the gut rather than by direct uptake from water.

In general, then, one would expect Co to be strongly bound to sediments in the aquatic environment, especially if manganese and iron oxides are present. Presumably, one could make the same statement about Co binding to soil in the terrestrial environment. As can be seen from Table B-1, the bioaccumulation factors for Co–57 presented there are within a factor of 5 of those for Cm–244.

B.3 MODELS USED TO STUDY TRANSPORT AND EFFECTS OF THE RADIONUCLIDES

PuO_2, including its transport in the environment, its uptake in the human body by ingestion or inhalation, and its fate following uptake, has been studied in great detail over the last 50 years. Models have been developed to determine the radiation dose from plutonium transport and uptake (e.g., NUS 1982; ICRP 1977; ICRP 1979;

TABLE B-1. COMPARISON OF SOME IMPORTANT ENVIRONMENTAL FACTORS FOR PLUTONIUM, CURIUM, AMERICIUM, AND COBALT

Environmental Transfer Factors	Pu–238	Cm–242	Cm–244	Am–241	Co–57
- Bioaccumulation in fish	3.5×10^{0}	2.5×10^{-1}	2.5×01^{-1}	2.5×10^{-1}	5.0×10^{1}
- Bioaccumulation in shellfish	1.0×10^{2}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{3}	2.0×10^{2}
- Soil-to-edible plant	2.5×10^{4}	2.5×10^{-3}	2.5×10^{3}	2.5×10^{-4}	9.4×10^{-3}

Source: Strenge and Peterson 1989

TABLE B-2. INTERNAL DOSE FACTORS[A]

Radionuclide	Pu–238		Cm–244		Co–57	
Half-life, years	87.7 (alpha)		19 (alpha)		0.73 (gamma)	
Chemical form	Dioxide		Unspecified (probably oxide)		Oxide	
Inhalation class	Y		W		Y	
Dose type/organ	Ingestion	Inhalation[b]	Ingestion	Inhalation[b]	Ingestion	Inhalation[b]
f_1 value	1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-3}	1.0×10^{-3}	3.0×10^{-1}	5.0×10^{-2}
CDE, rem/μCi[c]						
Lungs	—	1.2×10^{3}	—	—	5.9×10^{-4}	6.3×10^{-2}
Red Marrow	5.6×10^{-2}	2.4×10^{2}	3.3×10^{0}	3.7×10^{3}	1.0×10^{-3}	—
Bone Surface	6.7×10^{-1}	3.1×10^{3}	4.1×10^{1}	4.8×10^{3}	—	—
Liver	1.5×10^{-1}	6.7×10^{2}	9.6×10^{0}	1.1×10^{3}	1.7×10^{-3}	—
CEDE, rem/μCi[d]	5.4×10^{-2}	3.0×10^{2}	2.3×10^{0}	2.7×10^{2}	1.1×10^{-3}	7.5×10^{-3}

a. Source: ICRP (1979) and U.S. DOE (1988). The dose factors in the two references are consistent, except for Cm–244 ingestion factors for which U.S. DOE (1988) has been used. The latter are based on an f_1 value of 1.0×10^{-3} and are higher by a factor of 2 than those presented in ICRP-30, based on an f_1 factor of 10^{-4}.

b. Based on a particle size of 1 μm AMAD from ICRP-30.

c. Committed dose equivalent as defined in ICRP-30.

d. Committed effective dose equivalent using organ risk weighting factors as defined by ICRP-30.

ICRP 1990). Similar models are available for curium and cobalt. When developing those pathway, dosimetry, and risk models, the following factors are usually considered:

When a particular radionuclide enters the environment, a fraction of it is transported via air, groundwater, surface water, or foodstuffs to humans. Because Pu–238 has a relatively long radioactive half life (an initial quantity of Pu–238 will decay to 50 percent in 87.74 years), only about half of it will be removed from the environment by radioactive decay during a human lifetime. Cm–244 has a half life of 19 years, so that, in a typical human lifetime of 70 years about 90% will be removed from the environment. By contrast, Co–57 has a half-life of only 0.73 years, so that, after 10 years, 99.99% has decayed.

Parameters used for estimating the uptake from harvesting and consumption of agricultural products have been measured (Baes et al. 1984; Rupp 1980; Yang and Nelson 1984). These and similar agricultural and food consumption parameters and plutonium ingestion parameters (ICRP 1979) are used as the basis for estimating human doses via ingestion. For example, an analysis of Pu–238 contamination of orange trees shows that a total of only 1 percent of the plutonium actually aerially deposited on the plants would be transported on fruit from field to market during the following 12 months of harvesting (Pinder et al. 1987). Most of this plutonium would adhere to the fruit's peel and would be removed prior to ingestion; uptake to the orange itself would be extremely small or nonexistent.

A quantity of each radionuclide is inhaled or ingested and a fraction of it is transferred to the bloodstream and then to organs within the human body, retained in the lungs, or excreted. It is assumed for this analysis that other entry mechanisms in the body, such as injection, are not significant.

Plutonium resides in certain organs, principally the lungs, liver, and bone surfaces, for a long period of time (relative to human lifetimes) with a slow rate of excretion. Curium resides principally in the bone surfaces and liver. By contrast, the short-lived Co–57, is relatively rapidly excreted from the body. Apart from some accumulation in the liver, Co–57 tends to be uniformly distributed throughout the body. Its LET γ-emissions tend to irradiate the body uniformly, rather than to damage the cells in the immediate vicinity as do α-emitters.

Alpha radiation, characteristic of Pu–238 and Cm–244 irradiates nearby cells and cell components, such as chromosomes (genes), and a fraction of the cells are killed or damaged. Nevertheless, a large fraction of the damaged cells may survive (especially for single α-tracks that are the most likely in an affected cell nucleus; see Section B.5), and some undergo repair while others have defective repair and mutate.

Those mutated cells that do survive and reproduce may, after many years delay, produce significant detrimental effects in humans, including cancer and genetic abnormalities (germ cells). This fraction is the basis for the associated health risk discussed in the following sections.

Due to the extremely small amount of plutonium, cobalt, and curium transported to and accumulated in the human body from exposure to a postulated launch accident and the

stochastic (random) nature of the detrimental effects produced in irradiated cells, it is not possible to accurately predict the long-term effects of any one individual exposed during the postulated accident. However, it is possible to use the risk estimates experienced in a large exposed population to provide an estimate of the average risk to an individual (National Research Council 1988; National Research Council 1990). Detrimental effects, such as an increased rate of cancer, may possibly be predicted for a very large population also. From such estimates the average risk to a member of that population may also be calculated.

Dose equivalents to critical organs and tissues for all members of the general public exposed to the 99th percentile postulated accident involving a Mars Mission spacecraft would be many orders of magnitude below those that produce acute effects such as "radiation sickness," and even subtle acute effects such as changes in blood chemistry, should not be detectable.

B.4 TRANSPORT AND DEPOSITION OF RADIONUCLIDES IN THE HUMAN BODY

The ICRP has developed a widely accepted model for the distribution of inhaled and ingested radionuclides in the body. The ultimate fate of these radionuclides depends on such factors as particle size distribution, solubility, and chemistry. The ICRP model requires knowledge of numerous parameters, most of which are obtained empirically (e.g., there is no theoretical model for determining what fraction of ingested plutonium (say) enters the bloodstream). The required parameters are obtained from animal experiments and, if available, from human studies concerning the effects of nuclear weapons and of nuclear fallout. Of the transuranium elements, plutonium is by far the most widely studied.

B.4.1 Plutonium Dioxide

Plutonium dioxide that enters the human body by inhalation or ingestion has many possible fates, all of which have been studied in detail (ICRP 1979; ICRP 1986). The inhalation route is found to be approximately 1,000 times as effective as ingestion in transporting plutonium to the blood, due to the short time of residency, the chemical properties of plutonium, and the physiological environment of the gastro-intestinal (GI) tract (ICRP 1979).

Ingested plutonium dioxide would quickly pass through the digestive system and be excreted with only a small quantity being absorbed via the mucosa into the bloodstream. The fractional absorption of PuO_2 is estimated to average about 1 part in 100,000 ingested (ICRP 1979; ICRP 1986) – that is, in ICRP terminology, the f_1 factor for ingestion is 10^{-5}. The fractional absorption is based on the average individual. PuO_2 in the environment could become more soluble with time due to the use of fertilizers in gardening, chlorination in drinking water, and conversion to soluble forms in seawater. Dietary and physiological factors, such as fasting, dietary calcium deficiency, disease or intake of medications, may also change the fractional absorption (ICRP 1986).

Inhaled plutonium dioxide would be transported to one or more portions of the respiratory system depending on the particle size. Generally, most particles larger than 5 to 10 micrometers would be intercepted in the nasopharyngeal region and either

expelled or swallowed to pass through the digestive tract; what is not absorbed, would then be excreted. Particles smaller than about 5 micrometers would be transported to and remain in the trachea, bronchi, or deep lung regions. Particles reaching the deep lung would be cleared from the body much more slowly than those not entering the lung. For example, approximate micrometer-size PuO_2 particles would typically be cleared from the pulmonary area of the lung at the rate of 40 percent in the first day, and the remaining 60 percent cleared in 500 days (ICRP 1979). Particles captured in the mucous lining of the upper respiratory tract would be moved more rapidly to the pharynx, where they would be swallowed. Once swallowed, they would behave as if ingested.

Plutonium dioxide remaining in the lung would continuously irradiate lung tissue, and a small fraction would be transported over time directly to the blood or to lymph nodes and then to the blood. The estimated fraction of plutonium transferred directly from pulmonary lung tissues to the blood would be about 1 percent of the amount retained in the lungs, depending on the size distribution of ultra-fine particles. Smaller particles are likely to form over time from larger particles due to the natural fragmentation processes associated with radioactive decay and may also be transferred to the blood. Over a period of years, approximately 15 percent of the PuO_2 initially deposited in the lungs would be transferred to the lymph nodes. Of that, up to 90 percent would likely be retained in the lymph node with a 1,000 day half-life before being transferred to the blood (ICRP 1986). Overall, the plutonium dioxide f_1 factor for inhalation is the same as that for ingestion, 10^{-5}.

Once PuO_2 has entered the blood via ingestion or inhalation, it would circulate and be deposited primarily in the liver and skeletal system. It is currently accepted that plutonium transported by the blood is distributed to the following organs: 45 percent in the liver, 45 percent in the skeletal system, 0.035 percent in the testes and 0.011 percent in ovaries with a non-measurable amount crossing the placenta and available for uptake by the fetus. The remaining 10 percent of the activity in the blood is excreted through the kidneys and colon or deposited in other tissues (ICRP 1979; ICRP 1986).

The estimated residence time in the liver, skeletal system, and gonads are quite long. Current estimates for 50 percent removal times for plutonium are 20 years for the liver, 50 years for the skeleton, and an infinite retention time for the gonads.

B.4.2 Curium

Metabolic data for curium are provided by the ICRP (1980). Americium, which is chemically similar, has been studied more extensively. Based on animal experiments with both materials, ICRP recommends an f_1 factor for curium ingestion of $5x10^{-4}$ (i.e., nearly two orders of magnitude greater than that for plutonium oxide). This is a significant difference, meaning that even though curium may be ingested in smaller quantities than plutonium, the resultant doses to various organs of the body may be greater per quantity of material ingested. Once the curium has been absorbed into the bloodstream, it behaves much in the same way as does plutonium, principally affecting

the bone and the liver. ICRP recommends that the same metabolic model can be used for the two chemicals.

Experimental data show that compounds of curium, including the oxide, would be lost from the lung much more quickly than the corresponding compounds of plutonium. Thus, curium resides in the lung for a much shorter time and the radiation dose to the lung per curie inhaled is much smaller. However, a greater fraction of the curium is absorbed into the bloodstream, either directly from the lung or, as it is cleared from the lung and ingested, through the G.I. tract. The curium oxide f_1 factor for inhalation recommended by ICRP is also $5x10^{-4}$.

The values of f_1 actually used in the Mars Mission survey for both the inhalation and ingestion pathways are twice the value recommended by ICRP (1986): i.e., they are increased to 10^{-3}. This is based upon values of f_1 that have been recommended for use by U.S. DOE (1988).

B.4.3 Cobalt

The behavior of cobalt in the body is completely different from that associated with curium or plutonium (ICRP 1986). ICRP recommends an f_1 factor for ingestion of 0.3 (except for oxides and hydroxides, for which f_1 is 0.05; however, even though the cobalt is presumed to be in the form of an oxide after a fire or burn-up on reentry, f_1 is conservatively taken to be 0.3 in the Mars Mission analysis).

ICRP recommends Inhalation Class Y for oxides of cobalt, with an f_1 factor of 0.05.

Based on the ICRP ingestion model, of the cobalt entering the bloodstream, a fraction 0.5 would go directly to excretion and a fraction 0.05 to the liver. The remaining fraction of 0.45 would be distributed uniformly among all other organs and tissues of the body. Of cobalt translocated to any tissue of the body, fractions of 0.6, 0.2 and 0.2 would be retained with biological half lives of 6, 60, and 800 days, respectively. Cobalt is assumed to be retained in the bloodstream with a half-life of half a day.

B.4.4 Internal Dose Factors

The internal dose factors used for the Mars Mission study are summarized in Table B-2, which is taken from (USDOE 1999).

B.5 CANCER INDUCTION AND GENETIC EFFECTS

A nearby cell may be affected in several ways by the ejection of an alpha particle from a decaying Pu–238 or Cm–244 nucleus.

- The alpha particle entirely misses the cell and has no damaging effect.
- The alpha particle strikes the cell nucleus and kills it.
- The alpha particle strikes the cell nucleus, damaging the DNA, but the cell survives with one of the following results:

—The damaged DNA is correctly repaired before cell division with no lasting effects.

—The damaged DNA is not correctly repaired and the cell lives but does not reproduce and dies at the end of its life cycle (common for highly differentiated cells).

—The damaged DNA is not correctly repaired and the cell lives to pass on defective genes to future generations of cells (common for undifferentiated stem cells).

Recent in vitro cellular-level irradiation studies have indicated that undifferentiated cells (including human epithelial cells of the type commonly involved in many cancers and leukemias) can survive not just single, but also multiple α-tracks (Nagasawa and Little 1992; Kadhim et al. 1992; Evans 1992; Kadhim et al. 1994; Hei et al. 1997; Little 1997; Riches et al. 1997; Pugliese et al. 1997; Miller et al. 1999).

While these cellular studies provide information about cell survival in vitro after single and multiple α-tracks in cell nuclei, and the tumorogenicity of cells transformed by α-tracks in cell nuclei when transferred to immune deficient test mice, they do not address numerous other fundamental questions. For example, what is the efficiency of repair of DNA damage in all individual cells (the studies were focused on visibly transformed cells)? Further, no definitive conclusion can yet be drawn about the probability of DNA damage in individual cells resulting in cancer in humans. These studies, which used weakened cell lines and immune deficient animals to demonstrate tumorigenicity of transformed cells do not indicate what the results might be for normal cell lines and animals and humans, especially when cell doses are spread over a human lifetime rather than the lifetime of a few generations of individual cells.

The only clear result of this line of research that can be acknowledged at this time is that the assumption of linearity used in this EIS is supported by these studies at the cellular level. Further, the quality factor used for dose and human stochastic risk calculations in this EIS may overestimate the proper dose for cancer and other stochastic effects. As a result, the conservatisms indicated by these in vitro cellular-level studies are noted, but until a number of fundamental questions are answered, it is premature to make any changes in the generally accepted risk models currently employed.

Co–57 on the other hand undergoes conversion electron decays, producing a number of conversion and auger electrons as well as low energy X-rays and several gamma rays–it is not an alpha emitter. Because it only produces articles of low linear energy transfer, its dose per unit of inhaled activity is less that 0.1 percent that of an equal amount of either plutonium or curium. Given the small potential source term, Co–57 is not a significant contributor to either the radiation dose or possible risk associated with the 2001 NASA lander/rover mission (ICRP 1980; ICRP 1983).

B.6 CONSIDERATIONS SPECIFIC TO THE MARS MISSION

The modeling for the Mars Mission encompasses both short-term (during plume passage) and long-term (chronic exposure) pathways:

B.6.1 During Plume Passage

The predominant pathway during the passage of the airborne plume is inhalation. The important parameters in this calculation are the rate of dilution of the plume as it travels downwind, the deposition mechanisms that deplete the plume and leave radioactive material on the ground, and the rate of inhalation. All of these parameters and mechanisms are radionuclide independent. Therefore, on a per-curie released-basis, any radionuclide-specific differences between predicted radiation doses via this pathway are due entirely to the behavior in the body.

B.6.2 Chronic Exposure Pathways

The modeling included contributions due to resuspension, ingestion of vegetables, external exposure and seafood ingestion.

B.6.1.1 Resuspension

In principle, resuspension of materials deposited on the ground could be different for each of the three radionuclides that are under consideration. However, experimental data are not available with which to make such a distinction and, as noted above, the radioactive materials are agglomerated with other spacecraft structural materials that control properties such as the particle size distribution. Therefore, the same resuspension model was used for Pu, Cm and Co. For launch area accidents, the resuspension model is a well-established one that starts with an initial resuspension factor of 10^{-5} that decreases exponentially to 10^{-9} after 2 years and remains at 10^{-9} thereafter (Momeni et al. 1979 and Strenge and Bander 1981). For materials deposited after traveling more than 100 km from the source of a release, or released high in the atmosphere, the resuspension factor is 10^{-9} at all times (Bennett 1976 and UNSCEAR 1982). The resuspended materials would be inhaled and, again, radionuclide-specific differences in predicted doses would be entirely due to the behavior in the body.

B.5.2.2 Vegetable Ingestion

Four mechanisms of vegetable ingestion were taken into account as described below. For the *Nuclear Risk Assessment for the Mars 2001 Mission Draft Environmental Impact Statement* (USDOE 1999*)*, values of pathway parameters were taken from Momeni et al. (1979) and Strenge and Bander (1981).

- *Initial deposition immediately following the accident* – the amount initially deposited per curie released depends on non-radionuclide-specific factors such as particle size distribution and characteristics of the vegetation. The predicted amount of radioactive material ingested by humans then depends on assumptions about physical mechanisms and vegetable distribution that also do not depend upon the individual radionuclides, such as: the removal half-life for

leaf-deposited material (14 days), a leaf interception factor (0.5), and a vegetable density (2 kg/m^2). Harvesting and consumption are assumed to take place continuously during the 30-day period immediately following the release, such that the average contamination level would be the average over the 30-day period. Thus, on a per-curie released basis, radionuclide-specific differences are not a factor until the material has been ingested.

- *Continuous redeposition on the vegetables due to resuspension over the first 50 years following the accident* – the amount ingested by individuals is controlled by the resuspension mechanism (see above), the assumed dry deposition velocity (0.01 m/s) and assumptions about harvesting and distribution. Again, none of these factors is radionuclide-specific and differences in radiation doses arise because of half life or the fate of ingested radionuclides in the body.

- *Root Uptake* – this mechanism is in principle highly radionuclide and vegetable specific and depends on such factors as solubility, radionuclide chemistry and vegetable chemistry.

- *Rain Splashup* – these mechanisms depend in part on the characteristics of the soil and the rainfall. The model used for the Mars Mission is that due to Dreker (1984).

- *Relative Importance of the Vegetable Pathways* – Table B-2 (Bartram, 1980) shows the predicted relative importance of each of the vegetable pathways for a representative scenario.

- The most obvious feature of Table B-2 is that the initial direct deposition and the subsequent re-deposition by resuspension make up 95% or more of the contribution for each of the three radionuclides. These are the two pathways for which the modeling of what occurs between the point of release and the human receptor is controlled by non-radionuclide-specific mechanisms. Therefore, a detailed and accurate understanding of the mechanisms whereby these radionuclides move about in the environment and are taken up by plants and animals is not essential.

B.5.2.3 External Radiation

External radiation from material deposited on the ground and resuspended material is calculated using standard methods for cloudshine and groundshine. Because Pu–238 and Cm–244 are predominantly α-emitters, this exposure pathway is relatively unimportant. However, for Co–57, which emits γ-rays, the relative importance of this pathway is high (see Table B-3 below).

B.5.2.4 Seafood and Fish Pathway

Radiation doses can result from the bioaccumulation of Pu, Cm, or Co deposited on the surfaces of inland waters or oceans. Clearly, the predicted radiation doses arising from this pathway depend on a number of assumptions and physical and chemical processes, including; assumptions about how the deposited radionuclides are diluted in

TABLE B-3. REPRESENTATIVE RELATIVE VEGETABLE PATHWAY CONTRIBUTIONS BY RADIONUCLIDE

Vegetable Sub-Pathway	Fractional Contribution by Radionuclide		
	Pu–238	Cm–244	Co–57
Direct Deposition	6.36×10^{-1}	6.29×10^{-1}	6.09×10^{-1}
Re-Deposition by Resuspension	3.63×10^{-1}	3.59×10^{-1}	3.47×10^{-1}
Root Uptake	5.83×10^{-5}	5.83×10^{-4}	2.19×10^{-3}
Splashup	1.11×10^{-3}	1.11×10^{-2}	4.16×10^{-2}
Total	1.00×10^{0}	1.00×10^{0}	1.00×10^{0}

Source: USDOE 1999

TABLE B-4. Representative Relative Exposure Pathway Contributions by Radionuclide

Exposure Pathway	Fractional Contribution by Radionuclide		
	Pu–238	Cm–244	Co–57
On Grid			
Direct Inhalation	8.85×10^{-2}	8.22×10^{-2}	8.19×10^{-3}
Resuspension	9.10×10^{-1}	8.46×10^{-1}	6.37×10^{-2}
Vegetable	1.64×10^{-3}	7.22×10^{-2}	1.24×10^{-1}
Seafood	2.77×10^{-9}	1.22×10^{-7}	2.09×10^{-7}
External	1.41×10^{-4}	8.48×10^{-5}	8.04×10^{-1}
Total	1.00×10^{0}	1.00×10^{0}	1.00×10^{0}
Off Grid			
Direct Inhalation	9.28×10^{-1}	4.95×10^{-1}	9.92×10^{-3}
Resuspension	5.11×10^{-3}	1.52×10^{-3}	5.96×10^{-6}
Vegetable	2.09×10^{-2}	5.03×10^{-1}	1.74×10^{-1}
Seafood	3.04×10^{-8}	7.35×10^{-7}	2.53×10^{-7}
External	1.30×10^{-3}	4.27×10^{-4}	8.16×10^{-1}
Total	1.00×10^{0}	1.00×10^{0}	1.00×10^{0}

Source: USDOE 1999

the water; how the radionuclides are partitioned between water and sediment; how radionuclides are accumulated in different types of fish, crustaceans and mollusca.

B.5.2.5 Relative Importance of Each Pathway

The relative importance of each pathway discussed above is summarized in Table B-4. There are several pertinent observations about this table:

The seafood pathway is insignificant in all cases. This is due to a combination of: considerable dilution in the water; overwhelming partition into sediment, especially for the plutonium, for which the ratio of sediment concentration to water concentration is 10^5; and relatively small bioaccumulation factors.

For Co–57, the external irradiation pathway dominates, because, as noted above, Co–57 is a γ-emitter. As expected, the external irradiation pathway is a small contributor for Pu–238 and Cm–244 because these are α-emitters.

For the on-grid pathways, the resuspension pathways are by far the largest contributors for Pu–238 and Cm–244, with the direct inhalation and vegetable pathways being next in importance. As described above, these are all cases in which the movement of the radionuclides form the source of the accident to the human receptor is controlled by physical mechanisms and assumptions that are not radionuclide-specific.

For the off-grid case, the direct inhalation pathway is important for both Pu–238 and Cm–244. For the latter, the vegetable pathway is also a large contributor. Again, the transport to the receptor is controlled by non-radionuclide specific mechanisms.

In conclusion, the most important contributions arise from those pathways in which the transport from the accident scene to the human receptor are controlled by non-radionuclide-specific mechanisms. This means that differences in the radiation doses delivered by each radionuclide depend upon relatively well-understood factors: the initial amount of each radionucllde released; the half-lives; and the behavior in the body once inhaled or ingested as predicted by the well-established ICRP model. This is a most important conclusion when it comes to having confidence in the risk analysis.

B.6 REFERENCES FOR APPENDIX B

Aarkrog, A. 1977. “Environmental Behavior of Plutonium Accidentally Released at Thule, Greenland.” *Health Physics Society Journal,* Volume 32, pp. 271-284. April 1977.

Anspaugh, L., J. Shinn, P. Phelps, and N. Kennedy. 1975. “Resuspension and Redistribution of Plutonium in Soils.” *Health Physics Society Journal,* Volume 29*,* pp. 571-582. October 1975.

Baes, C., R. Sharp, A. Sjoreen, and R. Shor. 1984*.* “A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides Through Agriculture.” Oak Ridge National Laboratory, ORNL-5786. September 1984.

Bartram, B. 1999. *Private Communication*. TetraTech NUS Corporation, 1999.

Bennett, B.G. 1976. "Transuranic Element Pathways to Man." *Transuranium Nuclides in the Environment*, Symposium Proceedings, San Francisco, November 17-21, 1975, pp 367-383, International Atomic Energy Agency, 1976.

Choppin, G.R. and J.W. Morse. 1987. "Laboratory Studies of Actinides in Marine Systems." Environmental Research on Actinide Elements, Symposium Proceedings, Hilton Head, South Carolina, November 7-11, 1983. CONF 841142 (DE86008713), August 1987.

Dreker, M., T.E. Hakonson, G.C. White, and F.W. Whicker. 1980. "Rainsplash as a Mechanism for Soil Contamination of Plant Surfaces." *Health Physics*, Volume 38, No. 4, 1980.

Evans, J.H. 1992. "Alpha-particle After Effects." *Nature*, Volume 355, pp. 674-675. February 20, 1992.

Hei, T.K., Li-Jun Wu, Su-Xian Liu, Diane Vannais, Charles Waldren, and Gerhard Randers-Pehrson. 1997. "Mutagenic Effects of a Single and an Exact Number of α Particles in Mammalian Cells." Proceedings of the National Academy of Sciences, Volume 94, pp. 3765-3770. April 1997.

Interagency Nuclear Safety Panel (INSRP). 1989. *Safety Evaluation Report for the Galileo Mission*, Volumes 1 and 2. INSRP 89-01. May 1989.

Interagency Nuclear Safety Review Panel (INSRP). 1990. *Safety Evaluation Report for Ulysses Mission*, Volume 1 and 2. INSRP 90-01. September 1990.

International Commission on Radiological Protection (ICRP). 1977. *Recommendations of the International Commission on Radiological Protection*. ICRP Publication 26. 1977.

International Commission on Radiological Protection (ICRP). 1979. *Limits for Intakes of Radionuclides by Workers*. ICRP Publication 30, Part I, pp. 105-107. 1979.

International Commission on Radiological Protection (ICRP). 1980. *Limits for Intakes of Radionuclides by Workers,* Supplement of Part 1. ICRP Publication-30. 1980.

International Commission on Radiological Protection (ICRP). 1983. *Radionuclide Transformations-Energy and Intensity of Emissions.* ICRP Publication-38. 1983.

International Commission on Radiological Protection (ICRP). 1986. *The Metabolism of Plutonium and Related Elements*. ICRP Publication 48. 1986.

International Commission on Radiological Protection (ICRP). 1990. *1990 Recommendations of the International Commission on Radiological Protection*. ICRP Publication 60. 1990.

Kadhim, M.A., D.A. Macdonald, D.T. Goodhead, S.A. Lorimore, S.J. Marsden, and E.G. Wright. 1992. "Transmission of Chromosomal Instability after plutonium α-particle Irradiation." *Nature*, Volume 355, pp.738-740. February 20, 1992.

Kadhim, M.A., S. Lorimore, M.D. Hepburn, D.T. Goodhead, V.J. Buckle, and E.G. Wright. 1994. "Alpha-particle-induced Chromosomal Instability in Human Bone Marrow Cells." *The Lancet*, Volume 344, Number 8928, p. 987. October 8, 1994.

Little, John B. 1997. "What Are the Risks of Low-level Exposure to α Radiation from Radon?," Proceedings of the *National Academy of Science*, Volume 94, pp. 5996-5997. June 1997.

Miller, R.C., G. Randers-Pehrson, C.R. Geard, E.J. Hall, and D.J. Brenner. 1999. "The Onocogenic Transforming Potential of the Passage of Single α Particles through Mammalian Cell Nuclei." Proceedings of the *National Academy of Sciences*, Volume 96, pp. 19-22. January 1999.

Momeni, M.S., Y.Yuan, and A.J. Zielen. 1979. "The Uranium Dispersion and Dosimetry (UDAD) Code." Prepared for the U.S. Nuclear Regulatory Commission by Argonne National Laboratory, NUREG/CR-0553, May 1979.

Nagasawa, H., and J. Little. 1992. "Induction of Sister Chromatid Exchanges By Extremely Low Doses of α-Particles." *Cancer Research*, Volume 52, pp. 6394-6396. November 15, 1992.

National Aeronautics and Space Administration (NASA). 1989. *Final Environmental Impact Statement for the Galileo Mission (Tier 2)*. May 1989.

National Aeronautics and Space Administration (NASA). 1990. *Final Environmental Impact Statement for the Ulysses Mission (Tier 2)*. June 1990.

National Aeronautics and Space Administration (NASA). 1995. *Final Environmental Impact Statement for the Cassini Mission*. Office of Space Science, Solar System Exploration Division, NASA Headquarters, Washington, D.C. June 1995.

National Aeronautics and Space Administration (NASA). 1997. *Final Supplemental Environmental Impact Statement for the Cassini Mission*. Prepared for: NASA, Office of Space Science, NASA Headquarters, Washington, D.C. June 1997.

National Research Council. 1988. *Health Risks of Radon and Other Internally Deposited Alpha Emitters*. Report from the Committee on the Biological Effects of Ionizing Radiation (BEIR IV), National Academy Press, Washington, D.C. 1988.

National Research Council. 1990. *Health Effects of Exposure to Low Levels of Ionizing Radiation*. Report from the Committee on the Biological Effects of Ionizing Radiation (BEIR V), Board on Radiation Effects Research, Commission on Life Sciences. National Academy Press. Washington, D.C. 1990.

Noshkin, V.E., W.L. Robinson, K.M. Wong, J.L. Brunk, R.J. Eagle and H.E. Jones. 1997. "Past and Present Levels of Some Radionuclides in Fish from Bikini and Enewetak Atolls." *Health Physics*, Volume 73, pp.49-65, July 1997.

NUS Corporation. 1982. *Overall Safety Manual, Map of the Climates of the Earth*. Prepared by the Environmental Systems Group for the U.S. Atomic Energy Commission. 1982.

Pinder, J., and A. Doswell. 1985. "Retention of 238Pu-Bearing Particles by Corn Plants." *Health Physics Society Journal*, Volume 49, pp. 771-776. 1985.

Pinder, J., D. Adriano, T. Ciravolo, A. Doswell, and D. Yehling. 1987. "The Interception and Retention of 238Pu Deposition by Orange Trees." *Health Physics*, Volume 52, pp. 707-715. May 8, 1987.

Pugliese, M., M. Durantes, G.F. Grossi, F. Monforti, D. Orlando, A. Ottolenghi, and G. Gialanella. 1997. "Inactivation of Individual Mammalian Cells by Single α Particles." *Int. J. Radiat. Biol*., Volume 72, Number 4, pp. 397-407.

Riches, A.C., A. Herceg. P.E. Bryant, D.L. Stevens, and D.T. Goodhead. 1997. "Radiation-induced Transformation of SV40-immortalized Human Thyroid Epithelial Cells by Single Exposure to Plutonium α-particles in Vitro." *Int. J. Radiat. Biol*., Volume 72, No. 5, pp. 515-521.

Rupp, E. 1980. "Age dependent Values of Dietary Intake for Assessing Human Exposures to Environmental Pollutants." *Health Physics Society Journal*. Volume 39, pp. 151-163. August 1980.

Strenge, D.L. and T.J. Bander, 1981. "MILDOS – A Computer Program for Calculating Environmental Radiation Doses from Uranium Recovery Operations." Prepared for the U.S. Nuclear Regulatory Commission by Pacific Northwest Laboratory, NUREG/CR-2011, March 1981.

Strenge, D.L. and S.R. Peterson. 1989. "Chemical Data Bases for the Multimedia Environmental Pollutant Assessment System (MEPAS): Version I." Prepared for the U.S. Department of Energy by Pacific Northwest Laboratories, PNL-7145, December 1989.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. *Ionizing Radiation: Sources and Biological Effects*. New York, 1982.

U.S. Department of Energy (USDOE). 1987. *Environmental Research on Actinide Elements*, DOE 86008713. Washington, D.C. August 1987.

U.S. Department of Energy (USDOE). 1988. *Internal Dose Rate Conversion factors for Calculation of Doses to the Public*. DOE/EH-0071 (July 1988).

U.S. Department of Energy (USDOE). 1999. *Nuclear Risk Assessment for the Mars 2001 Mission Draft Environmental Impact Statement.* September 17, 1999 with amendments.

Yang, Y., and C. Nelson. 1984. *An Estimation of the Daily Average Food Intake by Age and Sex for Use in Assessing the Radionuclide Intake of Individuals in the General Population.* Prepared for the U.S. Environmental Protection Agency, Report 520/1-84-021. 1984.

This page intentionally left blank.

APPENDIX C

ENVIRONMENTAL JUSTICE ANALYSIS

This page intentional left blank.

APPENDIX C

ENVIRONMENTAL JUSTICE ANALYSIS

C.1 INTRODUCTION

Executive Order 12898, *Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations*, directs Federal agencies to identify and address, as appropriate, the disproportionately high and adverse health or environmental effects of their programs, policies, and activities on minority populations and low-income populations.

The Council on Environmental Quality (CEQ) has oversight responsibility for documentation prepared in compliance with the National Environmental Policy Act. In December 1997, the Council released its guidance on environmental justice (CEQ 1997). The Council's guidance was adopted as the basis for the information provided in this appendix.

This section provides data necessary to assess the potential for disproportionately high and adverse human health or environmental effects that may be associated with launch of the Mars Surveyor 2001 (MS 01) mission. Potentially affected areas examined in this Draft Environmental Impact Statement (DEIS) are circles of 100-km (62-mi) radius centered at the launch sites at Vandenberg Air Force Base (VAFB), California and the Cape Canaveral Air Station (CCAS), Florida.

C.2 DEFINITIONS AND APPROACH

C.2.1 Minority Populations

The following definitions of minority individuals and population are used in this analysis of environmental justice:

Minority Individuals: Persons who are members of any of the following population groups: Hispanic, Native American, Asian or Pacific Islander, or Black.

Minority Population: The total number of minority individuals residing within a potentially affected area.

Persons self-designated as Hispanic are included in the Hispanic population regardless of race. For example, Asians self-designated as Hispanic are included in the Hispanic population and not in the Asian Population. Data used to characterize minority populations in the year 1990 were extracted from Table P12 of Standard Tape File 3 published by the U.S. Bureau of the Census (DOC 1992). Data used for the projection of minority populations in California and Florida for the years 2001 and 2005 were extracted from the U.S. Census Bureau s worldwide web site:

http://www.census.gov/population/www/projections/stproj.html

C.3 LOW-INCOME POPULATIONS

Poverty thresholds are used to identify low-income individuals and populations (CEQ 1997). The following definitions of low-income individuals and population are used in this analysis:

Low-Income Individuals: Persons whose self-reported income is less than the poverty threshold.

Low-Income Population: The total number of low-income individuals residing within a potentially affected area.

Data for the analysis of low-income populations were extracted from Table P121 of Standard Tape File 3 (DOC 1992).

C.4 DISPROPORTIONATELY HIGH AND ADVERSE HUMAN HEALTH EFFECTS

Disproportionately high and adverse health effects are those that are significant (as employed by the National Environmental Policy Act, 40 CFR Part 1508, 1508.27) or above generally accepted norms, and for which the risk of adverse impacts to minority populations or low-income populations appreciably exceeds the risk to the general population.

C.5 DISPROPORTIONATELY HIGH AND ADVERSE ENVIRONMENTAL EFFECTS

Disproportionately high and adverse environmental effects are those that are significant (as employed by the National Environmental Policy Act), and that would adversely impact minority populations or low-income populations appreciably more than the general population.

C.6 METHODOLOGY

C.6.1 Spatial Resolution

For the purposes of enumeration and analysis, the U.S. Census Bureau has defined a variety of areal units (DOC 1992). Areal units of concern in this document include (in order of increasing spatial resolution) states, counties, census tracts, block groups, and blocks. The block is the smallest of these entities and offers the finest spatial resolution. This term refers to a relatively small geographical area bounded on all sides by visible features such as streets and streams or by invisible boundaries such as city limits and property lines. During the 1990 census, the U.S. Census Bureau subdivided the United States and its territories into 7,017,425 blocks. For comparison, the number of counties, census tracts, and block groups used in the 1990 census were 3,248; 62,276; and 229,192; respectively. In the analysis below, block groups are used throughout as the areal unit. Block groups generally contain between 250 and 500 housing units (DOC 1992).

C.6.2 Projections of Populations

Health effects were calculated for populations projected to reside in potentially affected areas during the years 2001 and 2005. Projections of the total population for individual states are available from both the U.S. Census Bureau and various state agencies (Campbell 1996). The U.S. Census Bureau also projects state populations by age, sex, race, and Hispanic origin for the years from 1995 to 2025. In order to project minority populations in potentially affected areas, minority populations determined from the 1990 census data were taken as a baseline. Then it was assumed that percentage changes in the minority population of each block group for a given year (compared to the 1990 baseline data) will be the same as percentage changes in the state minority population projected for the same year. An advantage to this assumption is that the projected populations are obtained with consistent method regardless of the state and associated block group involved in the calculation. A disadvantage is that the method is insensitive to localized demographic changes that could alter projections in a specific area.

The U.S. Census Bureau uses the cohort-component method to estimate future populations for each state (Campbell 1996). The set of cohorts is comprised of: (1) age groups from 1 year or less to 85 years or more, (2) male and female populations in each age group, and (3) racial and ethnic groups in each age group and sex (Hispanic, Asian, Black, Native American, and White). Components of the population change used in the demographic accounting system are births, deaths, net state-to-state migration, and net international migration. If P(t) denotes the number of individuals in a given cohort at time "t", then:

$$\mathbf{P(t) = P(t_0) + B - D + DIM - DOM + IIM - IOM} \qquad \textbf{(Eq. 1)}$$

where:

$P(t_0)$ = Cohort population at time $t_0 \leq t$. For this analysis, t_0 denotes the year 1990;

B = Births expected during the period from t_0 to t;

D = Deaths expected during the period from t_0 to;

DIM = Domestic migration expected into the state during the period from t_0 to t;

DOM = Domestic migration expected out of the state during the period from t_0 to t;

IIM = International migration expected into the state during the period from t_0 to t; and

IOM = International migration expected out of the state during the period from t_0 to t.

Estimated values for the components shown on the right side of equation 1 are based on past data and various assumptions regarding changes in the rates for birth, mortality, and migration (Campbell 1996). It should be noted that the U.S. Census Bureau does not project populations of individuals who identified themselves as "Other Race" (and non-Hispanic). This population group is less than 2 percent of the total population in each of the states. However, in order to project total populations in the environmental justice analysis, population projections for the "Other Race" group were made under the assumption that the

growth rate for the “Other Race” population will be identical to the growth rate for the combined minority and White populations.

C.6.2 Environmental Justice Assessment

The purpose of this analysis is to 1) identify minority populations and low-income populations residing that would be potentially affected by implementation of the proposed action or alternatives and 2) determine if implementation of the proposed action or alternatives would result in disproportionately high and adverse effects on these populations. Figures C-1 and C-2 show the potentially affected areas within a radius of 100 km (62 mi) of the launch sites in California and Florida, respectively.

C.7 CHARACTERIZATION OF POTENTIALLY AFFECTED POPULATIONS

C.7.1 Vandenberg Air Force Base

Figure C-3 shows the population residing in potentially affected area surrounding VAFB during the decennial census of 1990, as well as the population projected to reside in the area by the year 2001. Analogous data are shown in Figure C-4 for the year 2005. Table C-1 provides projected population estimates at distances of 10, 20 and 100 km (6, 12, and 62 mi) from the launch site for the years 2001 and 2005 compared to the levels determined in the decennial census of 1990. Minority residents comprised more than one-fourth of the population in the potentially affected area in 1990, and are projected to comprise more than one-third of the residents by the year 2001 rising to about 40 percent by 2005. Minority residents represented approximately 43 percent of California s population in 1990, and are projected to comprise over one-half of the State s population by the year 2001. Thus, in 1990, the percentage minority population residing in the potentially affected area was less than the corresponding percentage for the State of California and is projected to remain so through the year 2005.

In 1990 Hispanics formed over 75 percent of the minority population within 100 km (62 mi) and 20 km (12 mi) of the VAFB launch site. Current projections for 2001 and 2005 indicate that Hispanics will continue to constitute over 70 percent of the minority population within 100 and 20 km (62 and 12 mi) of the launch site. Within 10 km (6 mi) of the launch site, Hispanics constituted the largest portion (44 percent) of the minority population in 1990, followed closely by Blacks. By 2001, the Hispanic population is projected to grow to about 43 percent of the minority population within 10 km (6 mi) of the VAFB launch site followed by Blacks at about 36 percent of the minority population. This relationship is expected to continue into the year 2005.

In 1990 about 13 percent of the resident within 100 km (62 mi) of the VAFB launch site were reported to be below the 1990 poverty threshold (see Table 4-1). Closer to VAFB, the portion of the population below the 1990 poverty threshold dropped to about 5 percent within 10 km (6 mi) of the VAFB launch site.

FIGURE C-1. POTENTIALLY AFFECTED AREA SURROUNDING VANDENBERG AIR FORCE BASE

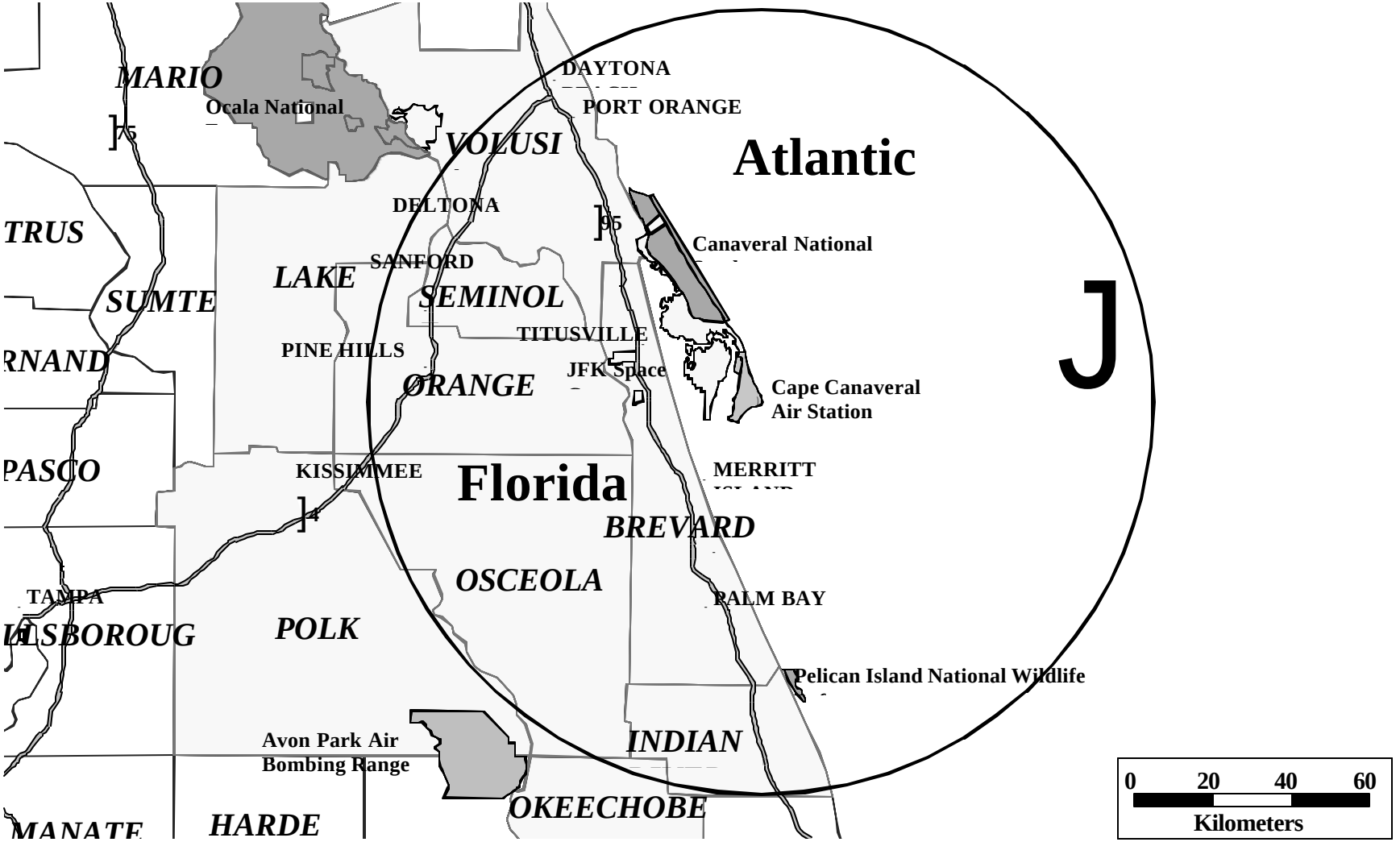

FIGURE C-2. POTENTIALLY AFFECTED AREA SURROUNDING CAPE CANAVERAL AIR STATION

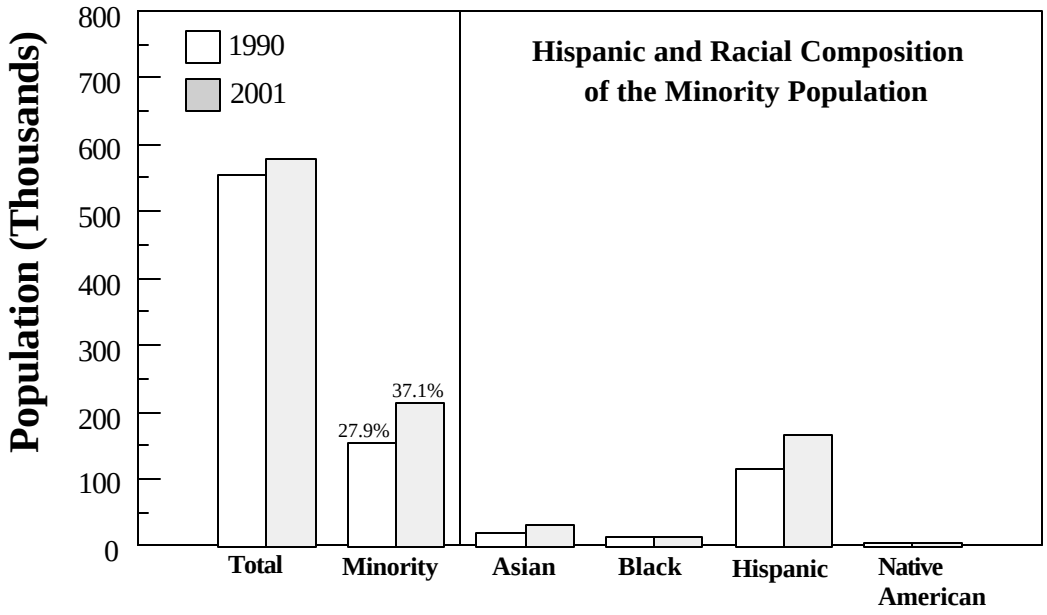

FIGURE C-3. POPULATIONS RESIDING WITHIN THE POTENTIALLY AFFECTED AREA SURRONDING VANDENBERG AIR FORCE BASE IN 1990 AND 2001

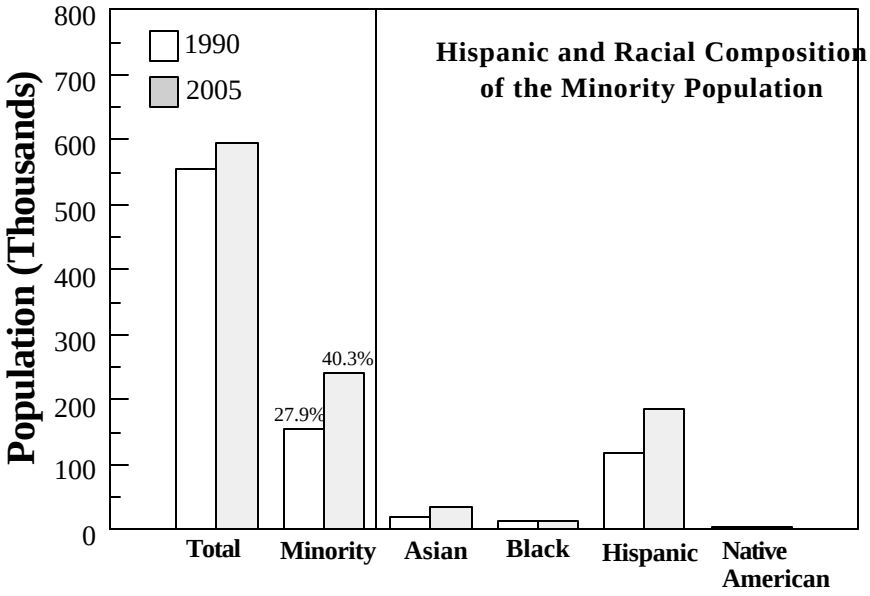

FIGURE C-4. POPULATIONS RESIDING WITHIN THE POTENTIALLY AFFECTED AREA SURRONDING VANDENBERG AIR FORCE BASE IN 1990 AND 2005

TABLE C-1. VAFB PROJECTED RACIAL AND ETHNIC COMPOSITION OF THE POPULATON AT VARYING DISTANCES FROM THE LAUNCH SITE, 2001 AND 2005

Population	100 km (62 mi)			20 km (12 mi)			10 km (6 mi)		
	1990	2001	2005	1990	2001	2005	1990	2001	2005
Asian	20,582	31,491	36,019	3,367	5,151	5,892	374	573	655
Black	13,786	14,062	14,200	4,467	4,557	4,601	1,130	1,152	1,164
Native American	4,137	3,765	3,641	713	649	628	93	84	82
Hispanic	116,321	165,175	186,113	14,140	20,077	22,622	978	1,389	1,565
Other Race	587	646	681	74	81	85	9	9	10
White	398,693	362,810	354,836	54,078	49,211	48,130	6,025	5,483	5,362
Minority	154,826	214,493	239,973	22,687	30,434	33,743	2,575	3,198	3,466
Total	554,106	577,949	595,490	76,839	79,726	81,958	8,609	8,690	8,838
Percent Minority	27.9%	37.1%	40.3%	29.5%	38.2%	41.2%	29.9%	36.8%	39.2%
Percent Low Income	13.1%			9.6%			5.1%		

C.7.2 Cape Canaveral Air Station

Figure C-5 shows the population residing in the potentially affected area surrounding CCAS during the decennial census of 1990, as well as the population projected to reside in the area by the year 2001. Analogous data are shown in Figure C-6 for the year 2005. Minority residents comprised approximately 19 percent of the population in the potentially affected area in 1990, and are projected to comprise approximately 23.0 percent of the residents by the year 2001 rising slightly to about 24 percent in 2005. Minority residents represented approximately 27 percent of Florida s population in 1990, and are projected to comprise over one-third of the State s population by the year 2001. Thus, in 1990, the percentage minority population residing in the potentially affected area was less than the corresponding percentage for the State of Florida and is projected to remain so through the year 2005. Hispanic and Black residents are the largest groups among the minority residents of the potentially affected area and the State of Florida. Growth rates in Hispanic and Asian residency for the State are projected to exceed those for all other groups.

During the 1990 Census, 10.1 percent of the residents within 100 km (62 mi) of the CCAS launch site reported incomes below the 1990 poverty threshold (see Table C-2). By comparison, the corresponding percentage for the State of Florida was 12.6 percent. Within 20 km (12 mi) about 8 percent of the population reported income below the 1990 poverty threshold, and within 10 km (6 mi) about 12.5 percent of the population was below the 1990 threshold.

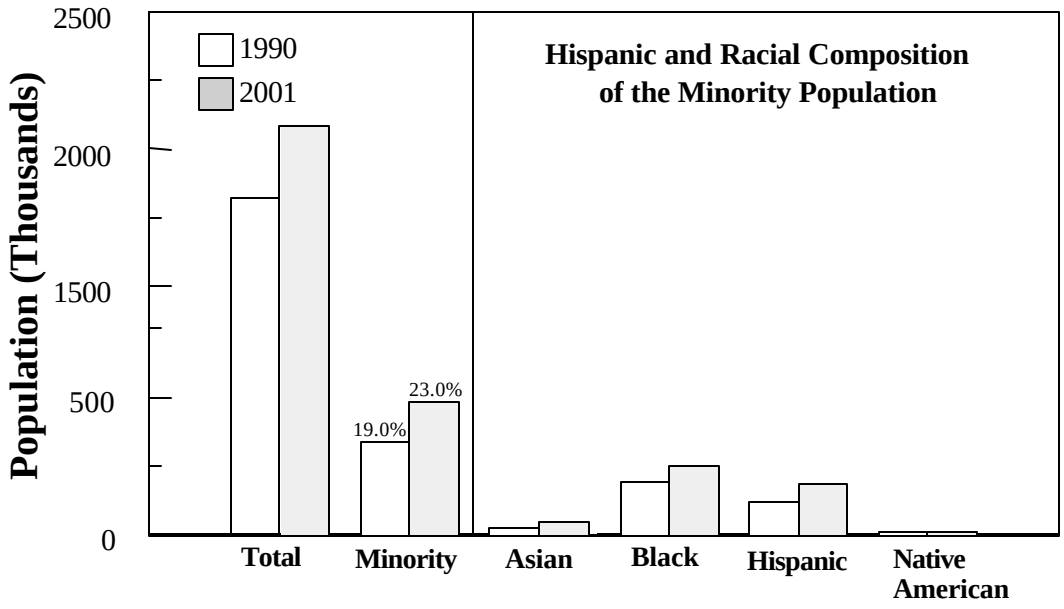

FIGURE C-5. POPULATIONS RESIDING WITHIN THE POTENTIALLY AFFECTED AREA SURRONDING CAPE CANAVERAL AIR STATION IN 1990 AND 2001

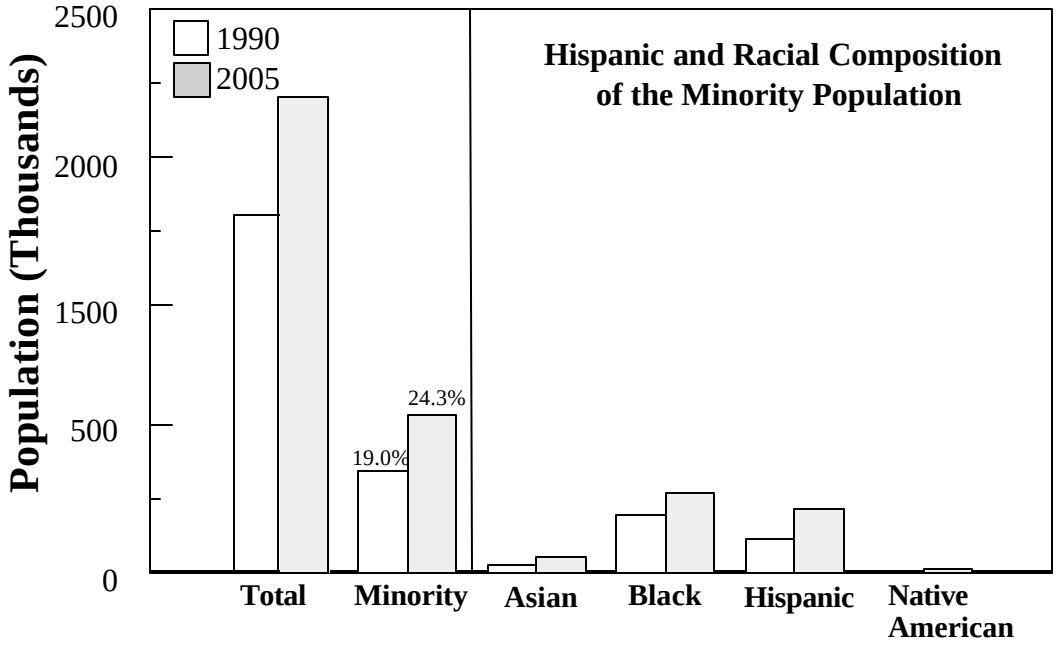

FIGURE C-6. POPULATIONS RESIDING WITHIN THE POTENTIALLY AFFECTED AREA SURRONDING CAPE CANAVERAL AIR STATION IN 1990 AND 2005

TABLE C-2. CCAS PROJECTED RACIAL AND ETHNIC COMPOSITION OF THE POPULATON AT VARYING DISTANCES FROM THE LAUNCH SITE, 2001 AND 2005

	100 km (62 mi)			20 km (12 mi)			10 km (6 mi)		
Population	**1990**	**2001**	**2005**	**1990**	**2001**	**2005**	**1990**	**2001**	**2005**
Asian	26,298	44,444	50,229	572	967	1,093	6	10	11
Black	191,118	246,543	263,743	1,940	2,502	2,667	101	131	140
Native American	5,982	7,179	7,538	305	365	384	47	57	59
Hispanic	116,100	183,438	210,141	1,558	2,462	2,820	140	221	253
Other Race	1,168	1,390	1,471	55	65	69	0	0	0
White	1,448,678	1,608,033	1,651,493	44,136	48,991	50,315	2,492	2,767	2,841
Minority	339,498	481,604	531,651	4,375	6,296	6,964	294	419	463
Total	1,789,344	2,091,027	2,184,615	48,566	55,352	57,348	2,786	3,186	3,304
Percent Minority	19.0%	23.0%	24.3%	9.0%	11.4%	12.1%	10.6%	13.2%	14.0%
Percent Low Income	10.1%	—	—	8.3%	—	—	12.5%	—	—

C.7 REFERENCES FOR APPENDIX C

Campbell, Paul R., 1996, *Population Projections for States by Age, Sex, Race, and Hispanic Origin: 1995-2025*, U.S. Bureau of the Census, Population Division, PPL-47, October.

Council on Environmental Quality (CEQ), 1997, *Environmental Guidance under the National Environmental Policy Act* (Available at http://www.Whitehouse.gov/CEQ/), Executive Office of the President, Washington, DC, December 10.

U.S. Department of Commerce (DOC), 1992, *1990 Census of Population and Housing, Summary Tape File 3 on CD-ROM*, Bureau of the Census, Washington, DC, May.

U.S. Department of Commerce (DOC), 1996, *Resident Population of the United States: Middle Series Projections, 2001-2005, by Sex, Race, and Hispanic Origin, with Median Age* (available at web site http://www.census.gov/population/projections/nation/nsrh/nprh0105.txt), U.S. Bureau of the Census, Washington, DC, March.

APPENDIX D

ECONOMIC IMPACTS ASSOCIATED WITH LAND CONTAMINATION

This page intentionally left blank.

APPENDIX D

ECONOMIC IMPACTS ASSOCIATED WITH LAND CONTAMINATION

D.1 INTRODUCTION

The following discussion of potential economic impacts is provided for illustrative purposes only. The U.S. Environmental Protection Agency (U.S. EPA) recommended guidance level for potential land contamination is used only as a theoretical basis for determining potential land area contamination that could be subject to some level of monitoring, remediation, or clean up thus providing a basis for this assessment. Thus this assessment is not intended to be a definitive statement.

After a radiological accident, there would be a cost for remediation of the affected area. It is likely that any area contaminated more than the recommended U.S. EPA guidance level of 7.4×10^3 Bq/m^2 (0.2 µCi/m^2) would be assessed and possibly remediated. The accident analysis in Section 4.1.5 states that the largest area that could be contaminated above this level would be less than 0.5 km^2 (0.19 mi^2) for mean or expectation releases for all postulated pre-launch and launch phase accidents, and less than 1 km^2 (0.39 mi^2) at the 99th percentile. This section provides an overview of estimated monitoring, characterization, and remediation costs for 1 km^2 (0.39 mi^2) (99th percentile) land areas contaminated at or above the recommended U.S. EPA guidance level as a result of a launch area accident provides an upper level approximation of potential costs.

Cost information was obtained from *Site Restoration: Estimation of Attributable Costs from Plutonium-Dispersal Accidents*, published by Sandia National Laboratories in 1996. Costs have been presented for four types of land: farmlands, rangeland, forests, and mixed-use urban areas. Farmlands are assumed to consist of land used for crops, livestock, farm machinery, and small towns. Rangeland is assumed to be mainly prairie with a low population density. Forests are assumed to be heavily vegetated areas. Mixed-use urban areas are assumed to contain a mix of residential, commercial, industrial, and unoccupied areas, as well as streets.

Costs were not estimated for wetlands. The ecosystem of a wetland is very diverse and complex and may be harmed more by decontamination operations than by allowing any contamination to remain in place. Additionally, wetlands have unique characteristics that could have a great impact on costs and would require site-specific information. The costs and benefits of decontamination of wetlands would have to be determined on a case-by-case basis.

D.2 ECONOMIC IMPACTS

The total remediation costs can be broken down into the individual costs of characterization, decontamination, and long-term monitoring.

D.2.1 Characterization

Before decontamination, characterization would be performed in order to assess the extent and nature of any contamination. Characterization activities could consist of ground or aerial surveys and air, soil, or water sampling. Table D-1 presents site characterization cost estimates for various types of land use.

TABLE D-1. SITE CHARACTERIZATION COSTS[a]

Land Type	$ million/km^2 (1995 dollars)
Farmlands	0.3
Rangeland	0.3
Forests	1.4
Mixed-Use Urban	0.8

Source: Chanin 1996

a. 1 km^2 = 0.39 mi^2

D.2.2 Decontamination

After characterization, contamination would be removed from land and buildings. A number of factors can affect the selection and cost of radiological mitigation activities, including the following:

- Initial Contamination Level and Area: Higher levels of initial contamination could require more sophisticated and more costly decontamination techniques to meet a particular cleanup standard than a lower level of initial contamination. Larger areas of contamination would be more expensive to decontaminate than smaller areas.
- Clean-up Standard: The applicable clean-up criteria would be site-specific and could be higher or lower than the U.S. EPA screening level. Site specific analyses would be required to estimate doses to cleanup workers and the public to determine the areas that should be remediated.
- Land Cover Type: The characteristics of some kinds of land covers make them more difficult and, therefore, more expensive to decontaminate (e.g., plowing and restoration of a natural vegetation area could be more costly than using the same technique in an agricultural area).
- Population Density and Distribution: A less populated area may require fewer emergency actions such as evacuations. Also, sparsely populated land would probably have fewer buildings and other large structures that would need to be decontaminated.
- Location: The location can affect the ease of access to the deposition (e.g., a steep hill slope could be more expensive to clean up than a level

field), as well as access to the site location and necessary decontamination resources, such as heavy equipment, water, and clean soil.

- Decontamination Method: More sophisticated decontamination methods (e.g., wetland restoration, soil stripping, or contaminant immobilization techniques) are generally much more expensive than simple actions, such as flushing surfaces with water.
- Disposal of Contaminated Materials: The disposal of contaminated vegetation and soils on site could be much more cost effective than the transportation and disposal of these same materials to a distant repository.

After an assessment of these factors, the appropriate methods of decontamination could be selected. Table D-2 presents examples of decontamination methods that might be used for various types of land. The total cost for decontamination would consist of the costs for the selected remediation actions plus the cost for disposal of any generated waste.

In the event of an accident, decontamination strategies would be chosen on location-specific basis. The highest priority of decontamination operations would be the health and safety of the public, followed by the resumption of CCAS regional activities. Areas above the U.S. EPA guideline level of 7.4×10^3 Bq/m^2 (0.2 µCi/m^2), corresponding to an additional annual individual risk of a radiation-induced cancer fatality of less than one chance in one million, would be evaluated for possible remedial action. It is assumed that any emergency actions such as evacuations may be taken immediately but decontamination would take place after planning, community input, and permit acquisition. For mixed-use urban areas, it is assumed that the buildings and structures would have deteriorated during the planning stage, and would have to be demolished and removed.

Table D-3 presents decontamination costs for various land types. The decontamination cost estimates include land acquisition, access control, emergency actions, decontamination, off-site waste disposal, site restoration, and final surveys and that remediation has been completed certification.

Decontamination of urban areas would most likely have to be carried out quickly with a shorter time allotted for planning. Decontamination methods are more successful for some surfaces, such as concrete and other porous materials, when performed shortly after deposition of the contamination.

Lightly contaminated areas are assumed to require a decontamination factor in the range of 2 to 5. Decontamination could consist of activities such as vacuuming, rinsing, and removing topsoil. Heavily contaminated areas are assumed to require a decontamination factor of more than 10. Structures and buildings would be demolished and removed, streets would be torn up, and topsoil would be removed. Table D-4 presents estimated costs for expedited decontamination of urban areas for lightly and highly contaminated areas.

TABLE D-2. POSSIBLE DECONTAMINATION METHODS

Land Use	Decontamination/Mitigation Methods
Farmlands	Locate and remove any detectable particles Rinse building exteriors and hard surfaces Deeply irrigate cropland Rinse or destroy crops Plow shallow areas Deconstruct and dispose of structures Restore habitat Ban future agricultural land uses
Rangeland	Locate and remove any detectable particles Rinse building exteriors and hard surfaces Rinse or remove vegetation Remove topsoil Plow shallow areas Deconstruct and dispose of structures Restore habitat Impose land use restrictions
Forests	Locate and remove any detectable particles Rinse or remove all vegetation Remove topsoil Relocate animals Restore habitat Impose land use restrictions
Urban	Locate and remove any detectable particles Rinse building exteriors and hard surfaces Rinse or remove vegetation Impose land use restrictions Deconstruct and dispose of structures Temporarily or permanently relocate affected population
Wetlands	Locate and remove any detectable particles Rinse or remove vegetation Dredge and dispose sediments Restore habitat Impose land use restrictions
Coastal/Ocean	Locate and remove any detectable particles Dredge and dispose of contaminated sediment Impose boating, shoreline, or land use restrictions

Source: Chanin 1996; NASA 1995

TABLE D-3. DECONTAMINATION COSTS[a]

Land Type	$ million/km^2 (1995 dollars)
Farmlands	73.5
Rangeland	71.9
Forests	130.8
Mixed-Use Urban	401.3

Source: Chanin 1996

a. 1 km^2 = 0.39 mi^2

TABLE D-4. EXPEDITED DECONTAMINATION COSTS FOR URBAN AREAS[a,b]

Usage Type	Lightly Contaminated ($ million/km^2) (1995 dollars)	Heavily Contaminated ($ million/km^2) (1995 dollars)
Residential[c]	75.2	306.0
Commercial[d]	195.3	851.2
Industrial[e]	674.0	1245.9
Streets	15.9	247.7
Unoccupied[f]	81.1	95.2
Mixed-Use[g]	127.4	396.2

Source: Chanin 1996

a. 1 km^2 = 0.39 mi^2
b. Lightly contaminated requires a decontamination factor of 2 to 5 to remediate; heavily contaminated requires a decontamination of 10 or more to remediate.
c. Consists of average single family homes
d. Consists of shopping areas and public non-recreational land
e. Consists of warehouse buildings
f. Parks and other recreational spaces
g. Consists of costs for other categories of urban land use multiplied by the percentage of occurrence of that type of land use

D.2.3 Long-Term Monitoring

After decontamination, a long-term monitoring program may be part of Federal or State requirements or part of the agreed-upon remediation plan. The monitoring program may include activities such as soil, air, or water sampling. Estimates of the annual cost for a monitoring program over a 1-km^2 (0.39-mi^2) area are presented in Table D-5.

TABLE D-5. MINIMUM MONITORING PROGRAM COST ESTIMATES

Period	Activity	Cost (FY 1994 $)
Year one	Transition from launch monitoring activity, plan development, supplemental equipment purchases, hiring of personnel	$1,240,000
Year two	Testing and shakedown of program methods and monitoring network, monitoring of mitigation actions	$620,000
Year three	Transition to long-term monitoring of impacts and mitigation actions	$310,000
Year four and each succeeding year	Program maintenance	$124,000

Source: NASA 1995

D.3 POTENTIAL ECONOMIC IMPACTS TO THE CCAS REGIONAL AREA

The CCAS regional area could be affected if an accident occurred in Phase 0 or 1 of the launch. Using the 99th percentile source terms provided in Table 4-10, the estimated amount of land that could be contaminated above the proposed U.S. EPA screening level would be about 1 km^2 (0.39 mi^2) or less for Phase 0 or 1 accidents. Using the costs presented in Table D-1, and assuming an affected area of 1 km^2 (0.39 mi^2), the characterization costs could range from about $300,000 for 1 km^2 (0.39 mi^2) of farmland or rangeland to $800,000 for 1 km^2 (0.39 mi^2) of mixed- use urban area, up to $1.4 million for 1 km^2 (0.39 mi^2) of forest area (1995 dollars). Using the costs presented in Table D-3, and again assuming an affected area of 1 km^2 (0.39 mi^2), the decontamination costs for 1 km^2 (0.39 mi^2) could range from about $71.9 million for farmland or rangeland to $131 million for forest area, up to $401 million for 1 km^2 (0.39 mi^2) of mixed-use urban areas (1995 dollars). The total cost, consisting of characterization plus decontamination costs for 1 km^2 (0.39 mi^2) of these three land use types, could range from about $72.2 million to $402 million (1995 dollars).

For expedited decontamination of urban areas, decontamination costs could range from about $15.9 million for light contamination of streets to $1.25 billion for heavy contamination of industrial areas (1995 dollars). For a mixed-use urban area, decontamination could range from approximately $127 million for light contamination to $396 million for heavy contamination (1995 dollars). The total cost, consisting of characterization plus decontamination costs, for a mixed-use urban area could range from about $128 million to $397 million (1995 dollars).

The cost for long-term monitoring would probably be higher at the beginning of the program and would decrease as the activities decrease. The total cost of monitoring over the longer term is unknown, since the duration of the monitoring is speculative.

D.4 POTENTIAL ECONOMIC IMPACTS TO THE GLOBAL AREA

Land contamination from the reentry of the RHUs from Earth orbit and their impact on a hard surface, such as rock, would be very small and extremely unlikely. Efforts would be made to find and survey any impact sites. The cost of these survey and monitoring efforts is speculative, although several million dollars would probably be expended. No significant land area would be expected to be contaminated above the U.S. EPA screening level.

D.5 REFERENCES FOR APPENDIX D

Chanin D.I., W.B. Murfin. 1996. Site Restoration: Estimation of Attributable Costs From Plutonium—Dispersal Accidents. Prepared for Transportation Systems Analysis Department, Sandia National Laboratories. Albuquerque, NM. May 1996.

National Aeronautics and Space Administration (NASA). 1995. Final Environmental Impact Statement for the Cassini Mission. Office of Space Science, Solar System Exploration Division, NASA Headquarters, Washington, D.C. June 1995.

This page intentionally left blank.

APPENDIX E

STRATOSPHERIC OZONE

This page intentionally left blank.

STRATOSPHERIC OZONE

APPENDIX E

STRATOSPHERIC OZONE

In the stratosphere, the primary environmental concern is the potential incremental effects of rocket motor emissions on the destruction of ozone. Before discussing the emission effects, brief descriptions of the stratosphere and the current understanding of natural and anthropogenic influences on ozone are provided.

The stratosphere

The lower boundary of the stratosphere is the tropopause. It marks the transition from the troposphere to the stratosphere. The altitude of the tropopause varies with latitude and season, but generally ranges from 16 kilometers (km) (10 miles, 100 hPa) in the tropics to 8 km (5 miles, 300 hPa) near the poles. The tropopause is generally marked by an abrupt change in the concentrations of trace constituents and by the disappearance of or a reversal of the vertical temperature gradient. Below the tropopause, in the troposphere, the air is moist and relatively ozone-poor, and convection efficiently mixes the air. Above the tropopause, in the stratosphere, the air is dry and ozone-rich, and vertical mixing is suppressed by the strong static stability.

Stratospheric ozone absorbs virtually all of the biologically harmful solar ultraviolet (UV) radiation with wavelengths less than 320 nanometers (nm). This absorption provides the source of heat which causes the temperature in the stratosphere to increase with height. The stratosphere is generally coldest at the tropopause and warmest at its upper limit, the stratopause. The stratopause is located near 50 km (30 miles, 1 hPa). Above the stratopause is the mesosphere, where both temperatures and ozone amounts fall with height. Thus natural and anthropogenic perturbations of stratospheric ozone influence the transmission of ultraviolet radiation to the ground and the thermal and dynamical climatology of the stratosphere.

Since temperature rises with height, the convection which is ubiquitous in the troposphere is nearly absent in the stratosphere. Whereas air parcels can traverse the depth of the troposphere in a few days, or in less than a few hours in deep convective clouds, it can take months or years to travel the same vertical distance in the stratosphere. This does not mean that stratospheric air is stagnant since air moves horizontally through wide ranges in latitude and longitude daily. It does mean that the evolution of stratospheric air depends not only on transport, but also on the photochemical time scales for each of an air parcel's chemical constituent.

Thus, the amount of ozone in a particular region of the stratosphere is determined by a balance between photochemical production and loss and transport by the stratospheric circulation. The tropical lower and middle stratosphere is the source region for ozone since photochemical production dominates loss. At high latitudes, loss dominates over production. The circulation, however, transports ozone toward the poles from the tropical

source region. So the actual concentration, the number of molecules per unit volume, is largest at middle and high latitudes in the lower stratosphere between 15 and 30 km (9 and 18.5 miles).

The amount of ozone above any particular location on the earth's surface is called total column ozone or, "total ozone." Globally averaged total ozone is about 300 Dobson[1] units (DU). Total ozone varies widely and cyclically by up to 10% daily due to passing weather systems and by up to 50% seasonally. Maximum values of total ozone occur over the northern polar regions in April and the southern middle latitudes in October (Bowman and Krueger 1985). Surface UV irradiance is proportional to the cosine of the zenith angle of the incident solar radiation and inversely related to the total ozone. On a given day in the absence of clouds and pollution, more UV reaches the ground with less total ozone.

Ozone production and loss

The production of ozone (O_3) is primarily due to the photodissociation of molecular oxygen (O_2) into two oxygen atoms (O + O) and their subsequent recombination with other O_2 molecules,

$$\mathbf{O + O_2 + M \rightarrow O_3 + M} \qquad \textbf{(Eq.1)}$$

In the above reaction M is a third molecule which carries away energy released in the reaction. Subsequently, O_3 absorbs a harmful UV photon and dissociates into O_2 and O. Again, the free O atom recombines quickly with another O_2 to form O_3. The probability of the three-body collision increases as one descends from the mesosphere into the stratosphere. Atomic oxygen is stable in the mesosphere but in the stratosphere it combines very rapidly to form ozone.

Loss of ozone in the stratosphere is much more complicated and is now known to be controlled by various sets of catalytic cycles involving molecular fragments, or "free radicals," of the nitrogen, chlorine, bromine, and hydrogen families. In a catalytic cycle, the catalytic molecule remains unchanged at the end of the cycle. An example is the breakdown of ozone via chlorine (C1):

$$Cl + O_3 \rightarrow ClO + O_2$$

$$ClO + O \rightarrow Cl + O_2$$

$$\text{Net: } \mathbf{O_3 + O \rightarrow O_2 + O_2} \qquad \textbf{(Eq.2)}$$

The ozone molecule is destroyed, but the Cl is not, and one Cl atom can be responsible for the loss of hundreds of thousands of ozone molecules before reacting with another atmospheric constituent and ending its catalytic loss cycle (Rowland and Molina 1975).

---

[1] One Dobson unit is defined to be 0.01 millimeter at standard temperature and pressure (i.e., all the ozone over a certain area is compressed down to 0° C and 1 atm pressure.

The gas-phase, or homogeneous, chemistry of the combined catalytic cycles were originally expected to exert the most influence on ozone loss in the upper stratosphere around 40 km (25 miles). Yet, the most pronounced local destruction of ozone occurs over Antarctica in the lower stratosphere between 12 and 25 km (7.5 and 15.5 miles) during the austral spring. Termed the "ozone hole," the cause is due chiefly to the appearance of polar stratospheric clouds (PSC). PSCs form in the extreme cold of winter lower stratosphere. On the surface of PSCs, a variety of reactions convert chlorine from rather inactive compounds to more reactive forms (Solomon 1990). An example is the reaction of HCl and chlorine nitrate ($ClONO_2$):

$$\mathbf{HCl + ClONO_2 \rightarrow Cl_2 + HNO_3} \qquad \textbf{(Eq.3)}$$

The chlorine molecule is then dissociated in the presence of sunlight and becomes available to participate in the gas-phase catalytic loss cycle. The PSC surface chemistry is called "heterogeneous," and these processes remove most of the Antarctic lower stratospheric ozone during early October. Over the northern high latitudes ozone losses in the winter and early spring are observed in about two-thirds of the years. But the magnitude of the loss is less than over the Antarctic due to a more variable meteorology which tends to prevent extremely cold conditions.

While production of stratospheric ozone is largely immune to anthropogenic influences, the loss of ozone is not. The levels of chlorine in the stratosphere have been steadily increasing over the past several decades and most of the chlorine in the stratosphere is now established as originating from manufactured compounds such as chlorofluorocarbons (CFCs) and carbon tetrachloride (World Meteorological Organization (WMO) 1999)). In the troposphere, these substances are inert. But in the stratosphere they are photodissociated, and the chlorine atoms which are released can then actively destroy ozone catalytically.

With the imposition of international protocols reducing the production of CFCs and halons, stratospheric chlorine plateaued at approximately 3.7 parts per billion by volume (ppbv) between mid-1992 and 1994 (WMO 1999). This is a significantly higher level of stratospheric chlorine than that observed prior to 1980. The anthropogenic loading has resulted in global ozone decreases during the past two decades. McPeters et al. (1996) report declines in total ozone at middle and high latitudes in both hemispheres. Current long-term trends at southern high latitudes average
-9% per decade and at northern high latitudes -5% per decade.

Efforts are now concentrated at detecting long-term changes in surface UV irradiance. Over Antarctica large increases are easily detectable because of the magnitude of the ozone loss. But at middle-latitudes, only a few stations offer sufficient record length or instrument stability to determine decadal changes. Those monitoring stations that do, are away from cities and air pollution. Clear-sky measurements at these stations show that total ozone decreases leading to UV-B increases are in good agreement with model calculations (WMO 1999).

Ozone loss in the stratosphere causes a net cooling of the stratosphere The effect is largest in the lower stratosphere where the temperature trend from 1979 to 1994 has been estimated at -0.6 K per decade. A cooler, lower stratosphere results in less infrared radiation reaching the troposphere. Radiative calculations suggest that since 1980, 30% of the temperature increase in the troposphere due to greenhouse gases has been offset by the radiative impact of stratospheric ozone loss (WMO 1999). Implications with respect to the climate of the stratosphere remain unresolved.

Rocket effects

A rocket affects the stratosphere in an immediate, episodic manner along the trajectory and in a long-term manner through dispersion of effluents by local turbulence and eventually by global transport. Within 1 km (0.54 nmi) of the plume for several minutes after passage of the launch vehicle, stratospheric chemistry is remarkably perturbed. But locally the extreme effects do not last more than hours. Winds tend to disperse the plume and dilute the effluents and combustion byproducts by mixing them with the ambient air. Since trajectories are not vertical it becomes difficult to detect column-integrated perturbations such as total ozone even within hours after launch. Within a few days the effluents are regionally and hemispherically dispersed. After months and years the effects are global but small, and must be considered in terms of the cumulative launch record to attain significance with respect to other natural and anthropogenic perturbations.

Gases

In the stratosphere the exhaust gases impact ozone destruction. Constituents of launch vehicle emissions which affect ozone most significantly are the chlorine compounds HCl and Cl_2. Nitrogen compounds (N_2, NO_X, (NO, NO_2, NO_3)), hydrogen compounds (H_2 and H_2O), alumina (Al_2O_3) particulates, ice and soot would play complicated and interactive, though by comparison, minor additional roles. Since ozone loss is expected to be largest from chlorine emissions (Jackman et al. 1996), studies generally focus on solid rocket motors (SRMs) which use ammonium perchlorate as the oxidizer.

These compounds must be deposited directly into the stratosphere to affect ozone. This is because exhaust species emitted into the troposphere are subject to photochemical oxidation and rainout before they can be transported to the stratosphere (WMO 1991). For example, NOx reacts photochemically to form nitric acid (HNO_3) and tropospheric ozone. HNO_3, as well as HCl and most inorganic chlorine (Cl_2, for example), react quickly to form water soluble compounds. These are then absorbed by cloud droplets and wash out of the troposphere in rain. Exhausted particulates, Al_2O_3, soot, and ice serve as cloud condensation nuclei, and soot is subject to oxidation by hydroxyl (OH), NO_X, and ozone (AIAA 1991). These processes remove most of the rocket emissions from the free troposphere in about a week (USAF 1998a) while the time scale for mass exchange between the upper (tropical) troposphere and lower stratosphere is roughly estimated at two years (Holton et al., 1995).

Ross et al. (1997b) measured significant ozone depletion in two plumes from daytime launches of Titan IV rockets. Between 30 and 60 minutes after launch, lower stratospheric

(18 km, 11 miles) ozone was nearly 100% depleted in the expanding rocket exhaust plume which reached 8 km (5 miles) across. After this time, ozone concentrations in the plume began returning to ambient levels. This generally corroborates detailed predictions from motor/nozzle and plume flow field computer codes. Within 1 km of the plume, Karol et al. (1992) simulated an 80% ozone depletion which would last for 1 to 3 hours. Denison et al. (1994) show similar effects on ozone in the rocket plume, but predicted the recovery to take several minutes instead of several hours. The difference between the two models' calculated depletion appears to be the choice of diffusion coefficient.

Danilin (1993) and Kruger (1994) investigate local ozone depletion in modeling experiments where the emitted Cl is divided between Cl_2 and HCl. Both find the ozone response sensitive to the amount of Cl_2 since Cl_2 is rapidly photolyzed to Cl atoms. Depletion is largest when a greater proportion of the emitted chlorine is Cl_2. Danilin (1993) finds that even if only a few percent of the emitted HCl is converted to Cl_2, then ozone depletion increases. Zittel (1994) modeled a substantial afterburning conversion of HCl to Cl and Cl_2 and the conversion had a strong height dependence. The percentage of HCl in the modeled emissions fell from about 75% in the lower stratosphere (15 km) to 20% in the upper stratosphere (40 km) while the proportion of Cl and Cl_2 combined rose from 20% to 70% over the same range of altitude. If the chlorine is emitted as purely HCl then the heterogeneous reactions on sulfuric acid aerosol are the most influential, although their effect is only marginally different from experiments without heterogeneous reactions (Danilin 1993). Denison et al. (1994) also find that heterogeneous chemistry is far less important than homogeneous chemistry on the time scales for the local plume.

The sensitivity of ozone loss to chlorine partitioning was recently addressed by direct lower stratospheric (19 km, 12 miles) Cl measurements from Ross et al. (1997a). A Titan IV plume was observed following a twilight launch and Cl_2 levels were elevated. This confirms that large fractions of HCl are converted to Cl_2 by afterburning. However, there was no measurable ozone loss in the plume. This suggests that sunlight is needed to drive the loss mechanism and that nighttime launches are a potential way to mitigate short-term local stratospheric ozone depletion in the rocket exhaust plume. The significance of chlorine-induced ozone loss relative to that due to NO_X and alumina led Ross et al. (1997b) to postulate a specific gas phase chlorine catalytic cycle to explain a discrepancy between the measured ozone loss and emitted reactive chlorine in the exhaust plume.

While there are no direct measurements of NO_X in plumes, numerical models indicate that small amounts are produced during some launches. The consensus among models is that it does not have as significant effect on stratospheric ozone destruction as does chlorine. In Zittel (1995), NO_X production is greatest near the ground, where the combined motor and afterburning produces NO_X flows of 1% of the total mass flow. For those motors with no nitrogen in the propellant, there is no NO_X at the nozzle exit. Any production by afterburning falls sharply with altitude to very small amounts at 20 km (12.5 miles) because the reaction which combines ambient N_2 with the atomic oxygen from combustion is highly temperature dependent and after burning temperature decreases with altitude. Denison et al. (1994) point out that at temperatures below 2000 K (1727 ºC) formation of NO_X is not favored. No detailed model calculations have assessed the impact of rocket-emitted NOx on ozone.

But since the mass of NOx emissions are expected to be small with respect to the mass of chlorine emissions, the impact of emitted NOx on ozone destruction is also expected to be comparatively small.

In part because of the uncertainty in the amount of Cl_2 in the exhaust, Aftergood (1991) speculates that the Total Ozone Mapping Spectrometer (TOMS) should be able to detect a total ozone "soft spot" of several tens of kilometers for several hours after launch. In the case where 2% of HCl is converted to Cl_2, Danilin (1993) computes a maximum total ozone decrease of 30 Dobson units over an area of 1600 km^2 (618 mi^2) six hours after a launch with a vertical trajectory. Such a perturbation could be seen by the TOMS. However, the actual trajectories are not vertical, the plumes are dispersed by turbidity, and the TOMS observation is likely to transect the trajectory. Syage and Ross (1996) addressed the detection issue with a chemical kinetics and dispersion model of a Titan IV plume. They simulated peak column ozone losses of 20% (69 DU) in an area several kilometers in radius. TOMS might detect this at the limit of its resolution as a 6 DU (2%) change. However, McPeters et al. (1991) find that the TOMS data do not find a measurable localized depletion following any of seven Space Shuttle launches.

Alumina

The potential for ozone loss due to the emitted alumina particles has long been considered a possibility and remains an area of active research. Hanning-Lee et al. (1996) discussed results of laboratory studies and provided predictions of ozone depletion due to alumina on both local and global scales. Heterogeneous processes on the alumina surfaces in or near the plume, modeled by Denison et al. (1994), show them to be ineffective in local destruction of ozone. On longer time scales, alumina particles dispersed throughout the stratosphere can potentially activate chlorine. Molina et al. (1997) expect the effect at high latitudes will be small because chlorine is activated more rapidly on PSCs. At middle latitudes, however, chlorine activation on alumina is substantially more probable than on the existing sulfate aerosol, suggesting that the SRM depletion potential is greater than that predicted on the basis of chlorine alone.

It is not known what happens to alumina particles after they are emitted. Molina et al. (1997) dismiss the likelihood that they coagulate with liquid H_2SO_4 aerosols which would eliminate their activation potential. Instead, they suggest that the particles remain able to promote chlorine activation throughout their residence time in the stratosphere. Zolensky et al. (1989) show increasing numbers of aluminum-rich particles in the lower stratosphere due to both exhausted alumina from SRMs and from spacecraft reentry and ablation. But size distribution, which determines residence time, number of particles, surface area, and ultimately the ozone depletion potential, is an area of disagreement. This is in part due to the few direct plume measurements
(Cofer et al. 1991, in the troposphere; Ross et al. 1999, in the lower stratosphere).

Nevertheless, current studies project minimal long-term impact on ozone.
Jackman et al. (1998a) adopted the trimodal size distribution of Brady and Martin (1995) in a set of computations which yielded only small long-term effects on stratospheric ozone from alumina emissions. Ross et al. (1999), from measurements in the lower stratosphere,

find significantly less mass in the smaller modes than did Brady and Martin (1995). Hence, they postulate a significantly reduced likelihood with respect to Jackman et al. (1998a) that emitted alumina would impact stratospheric ozone. Danilin (1993) considered three heterogeneous reactions which might proceed on the surfaces of alumina, but found that they do not play an important role on the time scales of the rocket plume.

Robinson et al. (1994) show that CFC-12 is decomposed on alumina surfaces. In Jackman et al.'s (1998a) model, including this process leads to a small decrease in ozone destruction associated with CFC-12. This is because tropospheric CFC-12 which comes into contact with the rocket exhaust would be decomposed on the alumina, thus would not be available for transport to the stratosphere.

Water

In the stratosphere the background water vapor concentration ranges from 3 parts per million by volume (ppmv) just above the tropopause to 6 ppmv in the upper stratosphere. Roughly half is due to vertical transport from the troposphere and half is due to oxidation of methane (CH_4) within the stratosphere (Chandra et al. 1997). Methane is mainly produced from anaerobic processes, and its atmospheric abundance is increasing. WMO (1994) estimates that two-thirds of the CH_4 comes from anthropogenic sources. CH_4 concentrations are expected to increase from the current 1.7 ppmv by 5 ppbv per year from 1990 to 2050. Since two H_2O molecules are produced from the oxidation of one CH_4 molecule, this would lead to a 10 ppbv (0.167%) per year increase in stratospheric H_2O. The frequency of occurrence of PSCs and the concentration of ozone-depleting hydrogen radicals would likely increase as a result of the additional H_2O burden.

The effects of rocket emissions on stratospheric water vapor are small, especially when compared to the ambient background amount. In addition to water vapor itself, combustion products which enhance H_2O are H, OH, HO_2, HCl, and molecular hydrogen, H_2. Assuming, as a worst case scenario, that all of these emissions are eventually converted to stratospheric H_2O, the long-term percentage increase in the global annual mean stratospheric water vapor, would be 1.18×10^{-9}% per kilogram of substance emitted. IPCC (1999) estimates that the globally averaged decrease in total ozone is 5.23×10^{-9}% per metric ton increase in stratospheric H_2O.

Soot

Ozone reacts heterogeneously with soot aerosol in the stratosphere. However, this is not a catalytic reaction since the soot is consumed. Carbon monoxide (CO) and carbon dioxide (CO_2) are formed as the byproducts. Although this process is relatively poorly understood at the present time, it is expected that the subsequent ozone loss is small (IPCC 1999).

Sulfur

In addition to the aluminum oxide aerosols, sulfur emissions from the burning of kerosene may contribute to the stratospheric sulfate aerosol (SSA) burden. As with the case of alumina, SSA provides surfaces on which heterogeneous reactions take place. At this time, the issue is being addressed comprehensively in the aircraft community and awaits

future assessments for rockets (Kawa et al. 1999). In some forms of aircraft-grade kerosene, sulfur may account for 0.06% of the mass fraction (IPCC 1999). Volcanoes inject large amounts of aerosol directly into the stratosphere and cause temporary global scale reductions in total ozone. The affect of sulfur aerosol from a single rocket is currently considered small compared to that of the chlorine emissions.

Long-term trends

For time scales beyond plume lifetimes, assessments must rely on multi-dimensional models. Since the effluents would be regionally and globally dispersed by the winds, the sharp ozone depletions predicted within the exhaust plume immediately following launch would quickly diminish during the following days and weeks. Prather et al. (1990) used a global, three-dimensional tracer transport model to simulate the evolution of enhancements to the stratospheric Cl for thirty days following a single shuttle launch. Two days after launch at 40 km altitude, Cl concentrations 30 pptv above background were predicted to spread over an area 20 degrees latitude by 30 degrees longitude. This would represent a local Cl increase of approximately 2% and the expected ozone decrease at that height was estimated to be 1%. At the end of the one-month integration, the injected Cl would be dispersed throughout the northern hemisphere and peak concentrations at 40 km would have fallen to 3 pptv (1%) above background. Thus, one month after launch, ozone levels in the upper stratosphere would be about 0.10 to 0.15% below pre-launch conditions and the depletion of total column ozone would also be similarly reduced to about 0.10 to 0.15% below pre-launch conditions (Prather et al., 1990).

For longer time scales, years and decades, assessments are currently provided by two-dimensional (averaged in longitude) models. These tools are considered adequate since Prather et al. (1990) show that Cl from a single launch would be distributed over all longitudes in a month (WMO 1999). Also, cumulative effects are of concern at these time scales, thus the emissions of several launch vehicles were incorporated into the modeling. The impact on ozone has usually been reported as a perturbation to the annually averaged global total ozone (AAGTO). Jackman et al. (1998a) calculated that the emissions from nine Shuttle and six Titan IV launches per year would reduce AAGTO by 0.033%. This simulation included gas phase reactions as well as heterogeneous chemistry for the sulfate aerosol layer, PSCs, and alumina. Jackman (1998b) provides the most recent calculation of the influence of the three most active compounds, HCI, NOx, and alumina, on AAGTO on the basis of a per-ton emission into the stratosphere. These are summarized in Table E-1.

TABLE E-1. PERCENT REDUCTION IN ANNUALLY AVERAGED GLOBAL TOTAL OZONE PER TON OF EMISSION INTO THE STRATOSPHERE

Compound	Percent Reduction
HCl	2.8×10^{-5}
Al_2O_3	7.5×10^{-6}
NO_X	1.6×10^{-6}

Source: Jackman 1998b

Three-dimensional models with both gas-phase and heterogeneous chemistry are now being aggressively developed. While these so-called chemistry and transport models (CTM) have been used to study issues such as the sensitivity of Arctic and Antarctic ozone loss to meteorological conditions and the impact of commercial aircraft in the stratosphere, generally they have not been integrated for periods long enough to meet the requirements for long-term assessments. Since there are considerable differences between individual CTMs, validation issues remain outstanding. Further development is required before a consensus will be reached on the long-term predictive capabilities of CTMs (WMO 1999).

Estimates of ozone depletion

Delta II 7925

Table E-2 uses the estimated total first-stage emissions provided in Table 4-1 of the text, and assumes all emissions migrate to the stratosphere representing a highly conservative upper limit. The three air-lit GEMs burn entirely in the stratosphere. The six ground-lit GEMs burn out and jettison at 28 km altitude after 86 seconds of flight. Thus a substantial portion of the ground-lit emissions are in the troposphere and subject to photochemical oxidation and rain out. The increase in stratospheric water, given the estimate rates presented earlier, would be negligible.

TABLE E-2. TYPICAL DELTA II 7925 EMISSION INFLUENCES ON STRATOSPHERIC OZONE

Launch Vehicle	HCl tons (kg)	Al_2O_3 tons (kg)	NO_X tons(kg)	Percent reduction in annually averaged global total ozone
Delta II 7925[a]	25 (22,284)	42 (37,900)	10 (8,696)	1.03×10^{-3}%

a. Assumes all emissions migrate to the stratosphere.

REFERENCES FOR APPENDIX E

Aftergood, S. 1991. Comment on 'The Space Shuttle's Impact on the Stratosphere' by Michael Prather et al. *Journal of Geophysical Research*, Vol. 96, pp. 17,377. 1991.

American Institute of Aeronautics and Astronautics (AIAA). 1991. "Atmospheric Effects of Chemical Rocket Propulsion." Report of an AIAA Workshop, Sacramento, California. 52p. June 1991.

Bowman, K.P., and A.J. Krueger. 1985. A Global Climatology of Total Ozone from the Nimbus 7 Total Ozone Mapping Spectrometer. *Journal of Geophysical Research*, Vol. 90, No. D5. pp. 7967-7976. August 20, 1985.

Brady, B.B., and L.R. Martin. 1995. Modeling Solid Rocket Booster Exhaust Plumes in the Stratosphere with SURFACE CHEMKIN. Report No. TR-5(5231)-9. The Aerospace Corporation, El Seguendo, CA. September 1, 1995.

Chandra, S., C.H. Jackman, E.L. Fleming, and J.M. Russell III. 1997. The Seasonal and Long Term Changes in Mesospheric Water Vapor. Geophysical Research Letters 24. pp. 639-642. 1997.

Cofer, W.R. III, G.C. Purgold, E.L. Winstead, and R.A. Edahl. 1991. Space Shuttle Exhausted Aluminum Oxide: A Measured Particle Size Distribution. *Journal of Geophysical Research*, 96. pp. 17,371-17,376. 1991.

Danilin, M.Y. 1993. Local Stratospheric Effects of Solid-Fueled Rocket Emissions. Ann. Geophys., Vol. 11. pp. 828-286. 1993.

Denison, M.R., J.J. Lamb, W.D. Bjorndahl, E.Y. Wong, and P.D. Lohn. 1994. Solid Rocket Exhaust in the Stratosphere: Plume Diffusion and Chemical Reactions. *Journal of Spacecraft and Rockets*, Vol. 31, pp. 435-442. May-June 1994.

Hanning-Lee, M.A., B.B. Brady, L.R. Martin, and J.A. Syage. 1996. Ozone composition on alumina: Implications for solid rocket motor exhaust. Geophysical Research Letters, Vol. 23. pp. 1961-1964. July 15, 1996.

Holton, J.H., P.H. Haynes, M.E. McIntyre, A.R. Douglass, R.B. Rood, and L. Pfister. Stratosphere-troposphere exchange. Reviews of Geophysics, 33, 4, pp. 403-39, November, 1995.

Inter-governmental Panel on Climate Change (IPCC). 1999. Special Report on Aviation and the Global Atmosphere. Cambridge University Press. 1999.

Jackman, C.H., D.B. Considine, and E.L. Fleming. 1996. Space shuttle's impact on the stratosphere: An update. *Journal of Geophysical Research*. Vol. 101, No. D7, pp. 12,523-12,529. May 20, 1996.

Jackman, C.H., D.B. Considine, and E.L. Fleming. 1998a. A Global Modeling Study of Solid Rocket Aluminum Oxide Emissions Effects on Stratospheric Ozone. Geophysical Research Letters 25. March 15, 1998.

Jackman, C.H. 1998b. Personal Communication from C.H. Jackman, National Aeronautics and Space Administration to J. Smith, Jet Propulsion Laboratory. Regarding current information on ozone depletion from launch vehicle emissions. March 18, 1998.

Karol, I.L., and O.E. Rozanov. 1992. Effect of space rocket launches on ozone. Ann. Geophys., 10. pp. 810-814. October 1992.

Kawa, S.R., J.G. Anderson, S.L. Baughcum, C.A. Brock, W.H. Brune, R.C. Cohen, D.E. Kinnison, P.A. Newman, J.M. Rodriguez, R.S. Stolarski, D. Waugh, and S.C. Wofsy. 1999. Assessment of the effects of high-speed aircraft in the stratosphere: 1998. NASA Tech. Rep. TP-1999-209237. Goddard Space Flight Center, Greenbelt, Maryland, June 1999.

Kruger, B.C. 1994. Ozone depletion in the plume of a solid-fueled rocket. Ann. Geophys., Vol. 12. pp. 409-416. 1994.

McPeters, R., M. Prather, and S. Doiron. 1991. Reply to comment on 'The space shuttle's impact on the stratosphere' by M.J. Prather et al. *Journal of Geophysical Research*. Vol. 96. pp. 17,279. 1991.

McPeters, R.D., S.M. Hollandsworth, L.E. Flynn, J.R. Herman, and C.J. Seftor. 1996. Long-term ozone trends derived from the 16-year combined Nimbus 7/Meteor 3 TOMS version 7 record. Geophysical Research Letters 23. pp. 2,699-3,702. 1996.

Molina, M.J., L.T. Molina, R. Zhang, R.F. Meads, and D.D. Spencer. 1997. The reaction of $ClONO_2$ with HCl on aluminum oxide. *Journal of Geophysical Research*. Vol. 24. pp. 1,619-1,622. 1997.

Prather, M.J., M.M. Garcia, A.R. Douglass, C.H. Jackman, M.K.W. Ko, and N.D. Sze. 1990. The Space Shuttle's impact on the stratosphere. *Journal of Geophysical Research*. Vol. 95. D-11, pp. 18,583-18,590. 1990.

Robinson, G.N., A. Freedman, C.E. Kolb, and D.R. Worsnop. 1994. Decomposition of halomethanes on alpha-alumina at stratospheric temperatures. Geophysical Research Letters 21. pp. 377-380. 1994.

Ross, M. N., J. O. Ballenthin, R. B. Gosselin, R. F. Meads, P. F. Zittel, J. R. Benbrook, and W. R. Sheldon. 1997a. In-situ measurement of Cl_2 and O_3 in a stratospheric solid rocket motor exhaust plume. Geophysical Research Letters, 24. pp. 1755-1758. 1997.

Ross, M. N., J. R. Benbrook, W. R. Sheldon, P. F. Zittel, and D. L. McKenzie. 1997b. Observation of stratospheric ozone depletion in rocket exhaust plumes. Nature, Vol. 390. pp. 62-64, 1997.

Ross, M.N., P.D. Whitefield, D.E. Hagen, and A.R. Hopkins. 1999. In situ measurements of the aerosol size distribution in stratospheric solid rocket motor exhaust plumes. Geophysical Research Letters 26. pp. 819-822. 1999.

Rowland, F.S. and M.J. Molina. 1975. Chloroflouromethanes in the environment. Rev. Geophys. Vol. 13. pp. 1-35. 1975.

Solomon, S. 1990. Progress toward a quantitative understanding of Antarctic ozone depletion. Nature. Vol. 347. pp. 347-354. 1990.

Syage, J. A., and M. N. Ross. 1996. An assessment of the total ozone mapping spectrometer for measuring ozone levels in a solid rocket plume. Geophys. Res. Lett., 23. pp. 3227-3230. 1996.

U.S Air Force (USAF). 1996. Final Environmental Assessment for the Delta III Launch Vehicle Program, Cape Canaveral Air Station. Prepared for the Department of the Air Force, 45th Space Wing. Prepared by McDonnell Douglas Aerospace Space and Defense Systems. April 1996.

U.S Air Force (USAF). 1998. Final Environmental Impact Statement- Evolved Expendable Launch Vehicle Program. HQ USAF/ILEVP, 1260 Air Force Pentagon, Washington, D.C. April 1998.

World Meteorological Organization (WMO). 1992. Scientific assessment of ozone depletion: 1991 World Meteorological Organization. Global Ozone Research and Monitoring Project. Geneva, Switzerland. Report No. 25. 1992.

World Meteorological Organization (WMO). 1995. Scientific assessment of ozone depletion: 1994 World Meteorological Organization. Global Ozone Research and Monitoring Project. Geneva, Switzerland. Report No. 37. 1995.

World Meteorological Organization (WMO). 1999. Scientific assessment of ozone depletion: 1998 World Meteorological Organization. Global Ozone Research and Monitoring Project. Geneva, Switzerland. February 1999.

Zittel, P.F. 1994. Computer Model Predictions of the Local Effects of Large, Solid-fueled Rocket Motors on Stratospheric Ozone. Aerospace. Report No. TR-94 (4231) –9. The Aerospace Corporation, El Seguendo, California. September 10, 1994.

Zittel, P.F. 1995. Computer Model Calculations of NO_x Production in Rocket Motors and Plumes. Aerospace Report No. TOR-96 (1306)-1. The Aerospace Corporation, El Seguendo, California. November 30, 1995.

Zolensky, M.E., D.S. McKay, and L.A. Kaezor. 1989. A tenfold increase in the abundance of large solid particles in the stratosphere as measured over the period 1976-1984. *Journal of Geophysical Research*. Vol. 94. pp. 1,047-1,056. 1989.

ACRONYMS FOR APPENDIX E

AAGTO	annually averaged global total ozone
Al_2O_3	aluminum oxide
CFC	chlorofluorocarbon
CH_4	methane
Cl	chlorine atom
Cl_2	chlorine
ClO	chlorine monoxide
$ClONO_2$	chlorine nitrate
CO	carbon monoxide
CO_2	carbon dioxide
CTM	chemistry and transport models
DU	Dobson Units
GEM	graphite epoxy motor
H_2	hydrogen
H_2O	water
H_2SO_4	sulfuric acid
HCl	hydrochloric acid or hydrogen chloride
HNO_3	nitric acid
HO_2	hydroperoxyl radical
hPa	hectopascal
K	degree Kelvin
km	kilometers
km^2	square kilometer(s)
LOX	liquid oxygen
mi	mile
mi^2	square mile(s)
N_2	nitrogen
nm	nanometers
nmi	nautical miles
NO	nitric oxide
NO_x	nitrogen oxides
O_2	oxygen
O_3	ozone
OH	hydroxide ion
ppbv	parts per billion by volume
ppmv	parts per million by volume
pptv	parts per trillion by volume
PSC	polar stratospheric clouds
RP-1	rocket propellant- 1
SRM	solid rocket motor
SSA	stratospheric sulfate aerosol
TOMS	Total Ozone Mapping Spectrometer
UV	ultraviolet